

NuFact15



The Muon Accelerator Program and the Muon Ionization Cooling Experiment

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*with acknowledgments to the MAP and MICE
Collaborations*



Outline



- Muon Accelerator Capabilities
- Why Neutrino Factories?
 - Neutrino Factory Concepts
 - Short baseline \Rightarrow vSTORM
 - Long Baseline \Rightarrow IDS-NF and NuMAX
- Going Beyond a Neutrino Factory Facility
 - Possibilities for a future Muon Collider Capability
 - Higgs Factory to >5 TeV
- Key Elements of the MAP R&D Effort
- The MICE Cooling Demonstration
- Conclusion



Muon Accelerators for HEP



- μ – an elementary charged lepton:
 - 200 times heavier than the electron
 - $2.2 \mu\text{s}$ lifetime at rest
- Physics potential for the HEP community using muon beams
 - Tests of Lepton Flavor Violation
 - Anomalous magnetic moment \Rightarrow hints of new physics ($g-2$)
 - Equal fractions of electron and muon neutrinos at high intensity –
the Neutrino Factory concept
Precision oscillation physics, sensitivity to probe new physics
 - Large coupling to the “Higgs mechanism”
 - $\mu^+\mu^-$ collider \Rightarrow **precision leptonic probe of fundamental interactions**

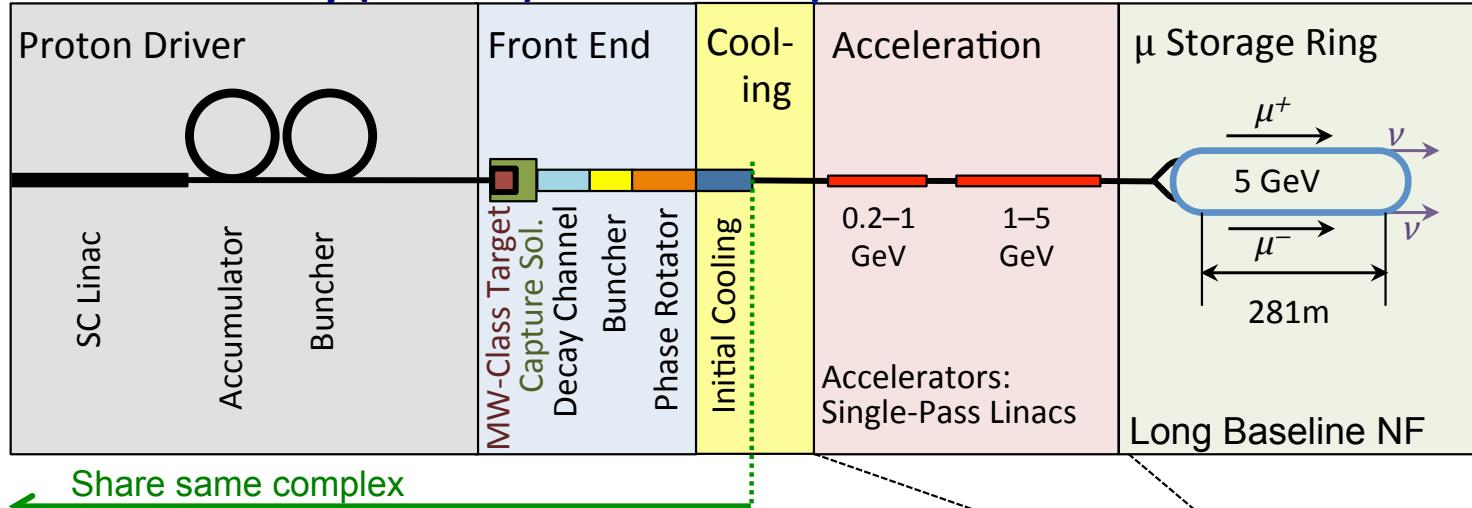
$$\begin{aligned}\mu^+ &\rightarrow e^+ \nu_e \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- \bar{\nu}_e \nu_\mu\end{aligned}$$

$$\sim \left(\frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$$

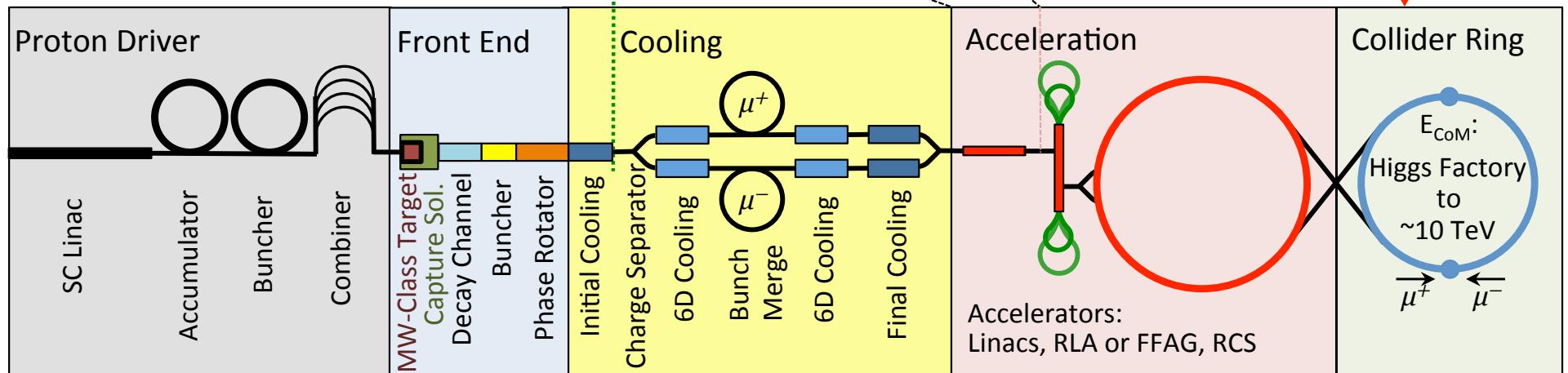


Muon Accelerator Capabilities for HEP

Neutrino Factory (NuMAX)



Muon Collider





WHY NEUTRINO FACTORIES?



The Critical Issues



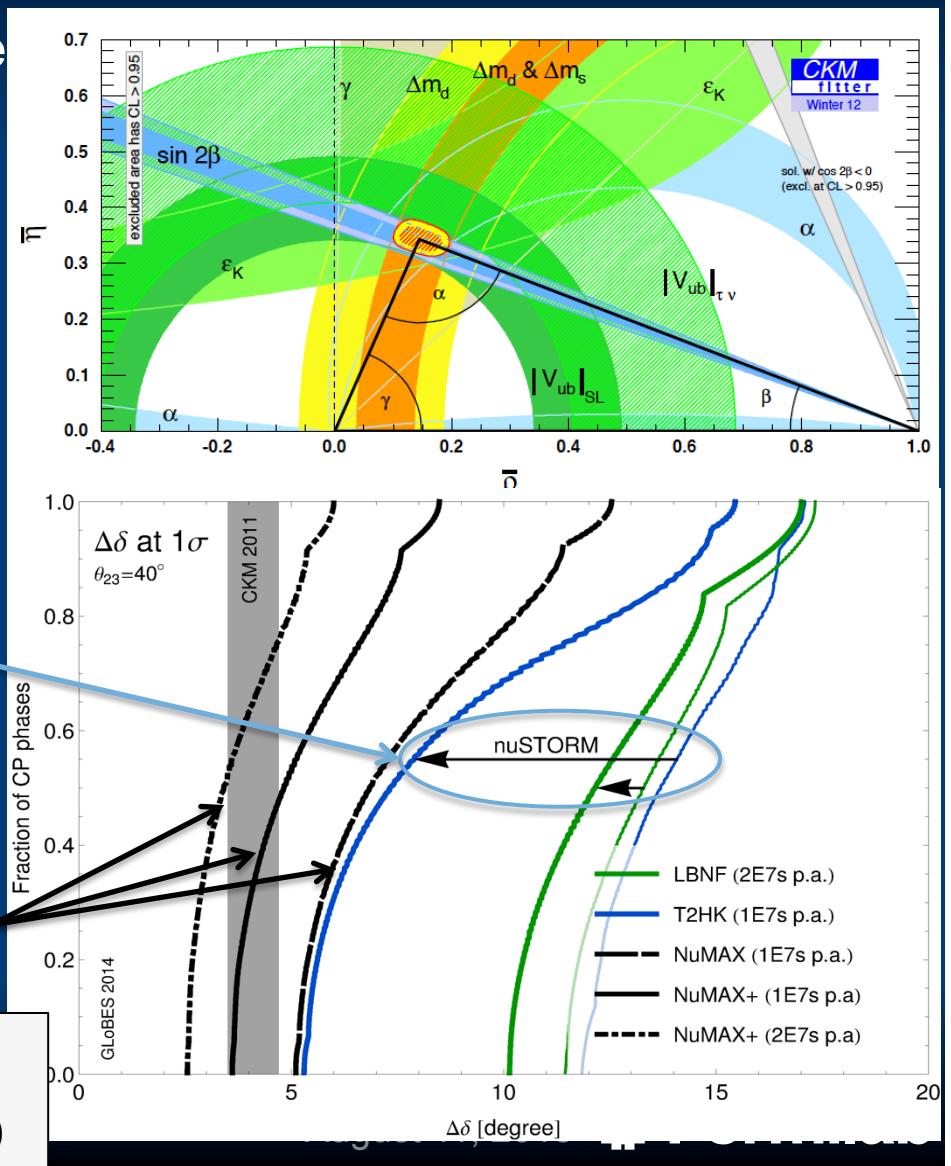
- What must we understand in the neutrino sector?

- δ_{CP} : Can this be done with the same precision as the quark sector???
- The mass hierarchy
- The value of $\theta_{23}-\pi/4$: +, - or zero?
- Resolve the LSND and other short baseline experimental anomalies
- And enable the search for new physics

Impact of precision short-baseline NF capabilities

Impact of precision long-baseline NF capabilities

GLoBES Comparison of Potential Performance of the Various Advanced Concepts (courtesy P. Huber)





Microscopes for the ν Sector

- Superbeam technology will continue to drive observations in the coming years
- *However, anomalies and new discoveries will drive our need for precision studies to develop a complete physical understanding*
- Neutrino Factory capabilities (both long- and short-baseline) offer the route to *controlled systematics* and *precision measurements*, which are required to fully elucidate the relevant physics processes

⇒ *Precision Microscopes for the ν sector*



Current Neutrino Factory Thrusts

- Short Baseline NF
 - nuSTORM
 - Definitive measurement of sterile neutrinos
 - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
 - *Beam line concept \Rightarrow higher purity beams for current experimental program*
 - HEP muon accelerator proving ground...
 - Long Baseline NF with a Magnetized Detector
 - IDS-NF (International Design Study for a Neutrino Factory)
 - 10 GeV muon storage ring optimized for 1500-2500 km baselines
 - “Generic” design (ie, not site-specific)
 - NuMAX (Neutrinos from a Muon Accelerator CompleX)
 - Site-specific: FNAL \Rightarrow SURF (1300 km baseline)
 - 4-6 GeV beam energy optimized for CP studies
 - Flexibility to allow for other operating energies
 - Can provide an ongoing, high statistics, short baseline measurement option
 - Magnetized Detector
 - LAr is the goal but magnetized Fe provides equivalent CP sensitivity with $\sim 3x$ the mass

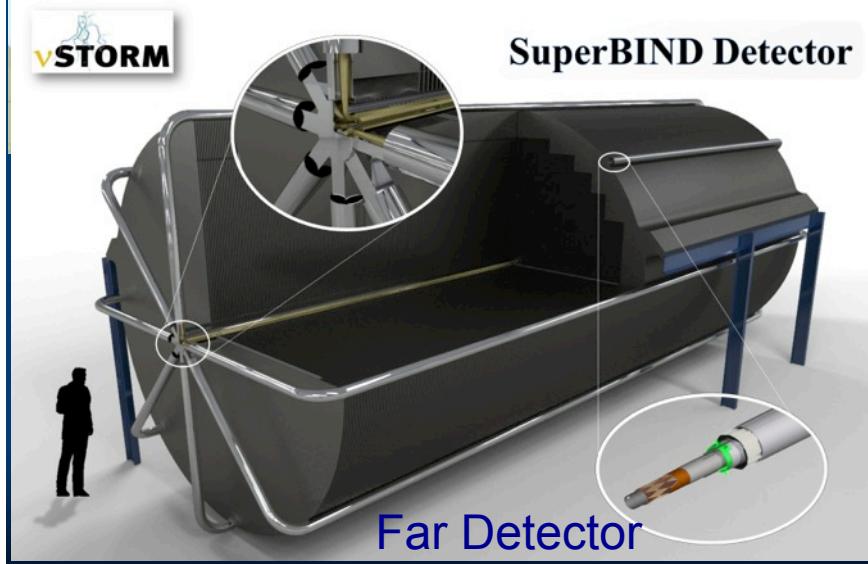
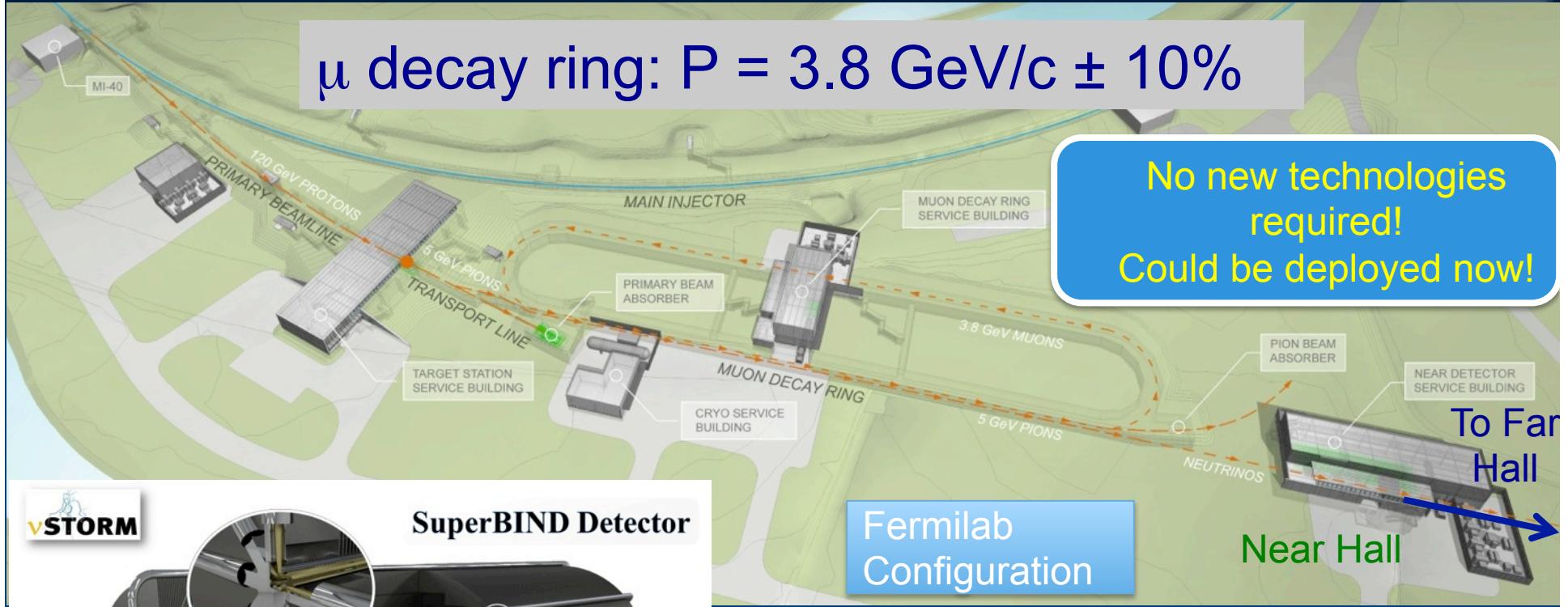


vSTORM – the First NF?



μ decay ring: $P = 3.8 \text{ GeV}/c \pm 10\%$

No new technologies required!
Could be deployed now!



Fermilab Configuration

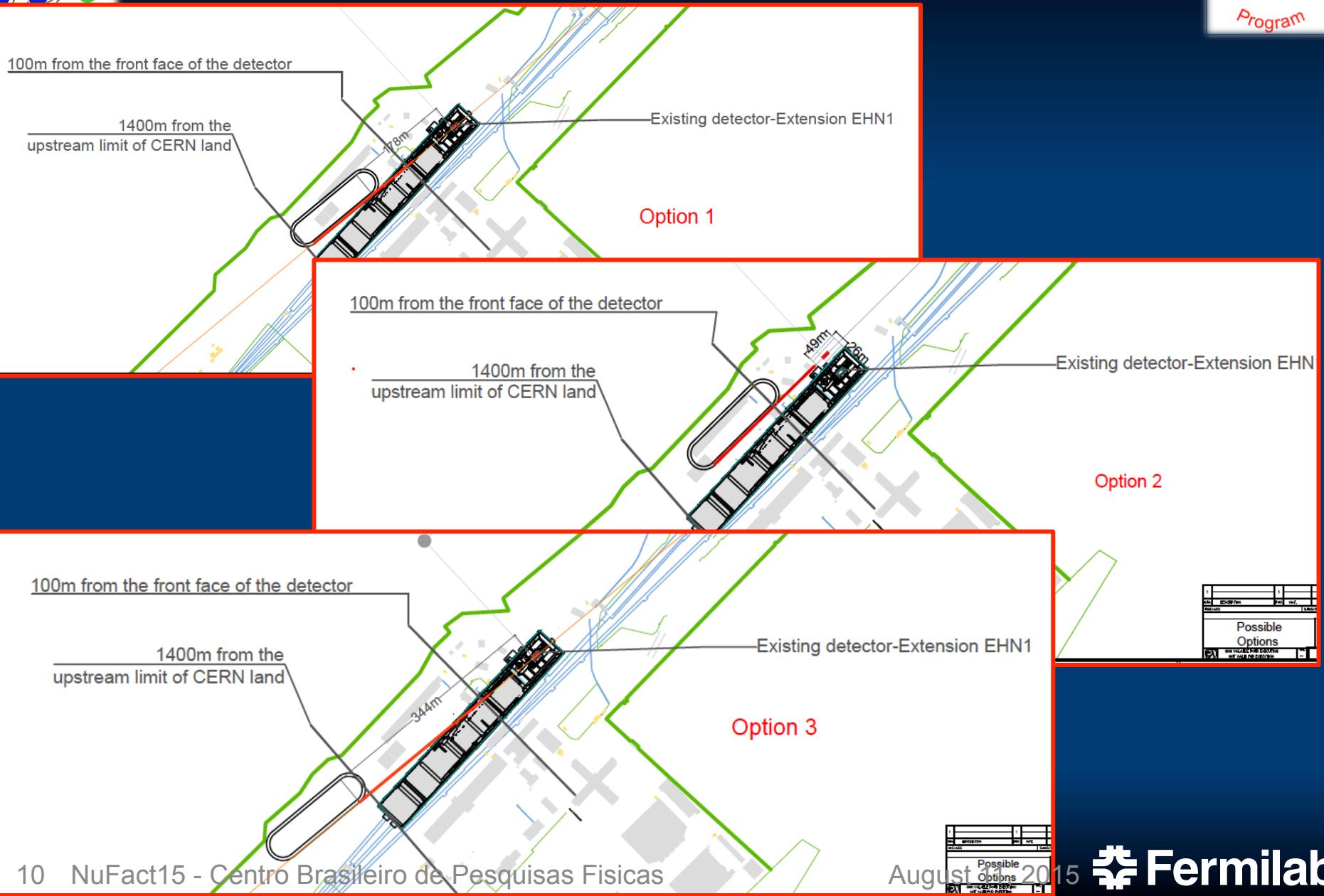


Far Hall @ 1.9km



vSTORM Option for the CERN Neutrino Platform

under study: M. Nessi, et al.

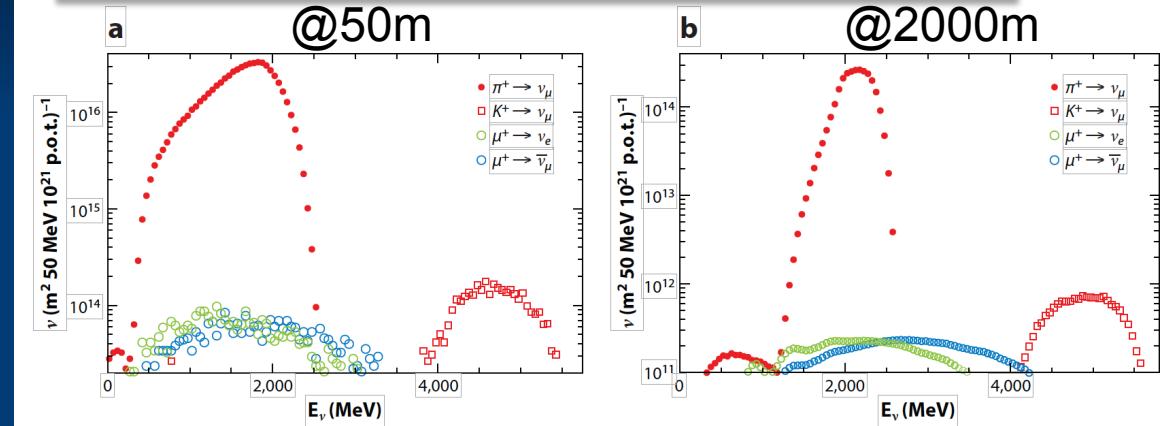




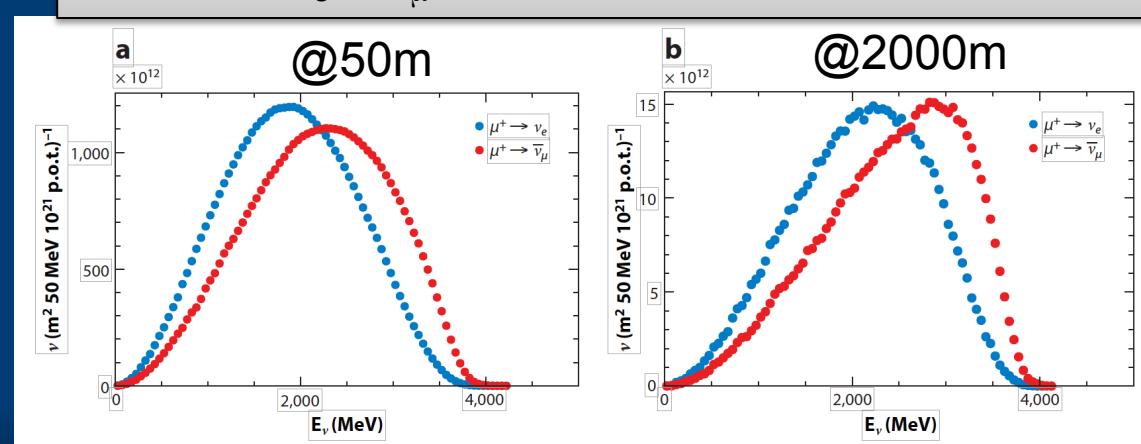
ν Beams at nuSTORM

- ν beams from π decay at nuSTORM:
High flavor purity with flux known to <1%
Source of beam line concept (e.g., nuPIL, enhanced MOMENT concept)

$\pi^+ \rightarrow \mu^+ + \nu_\mu$, π decays in injection straight



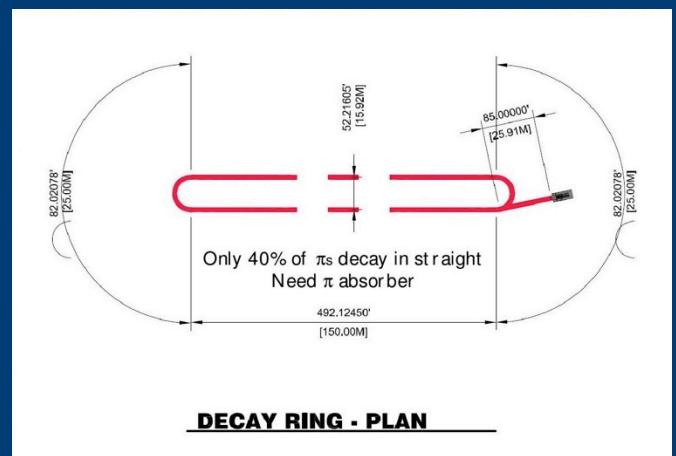
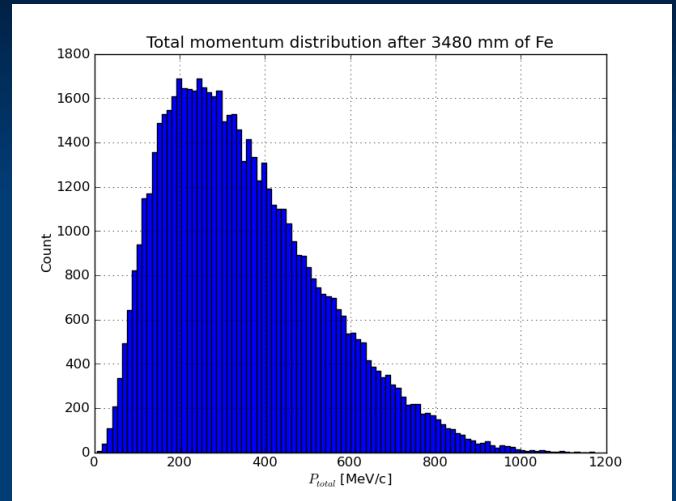
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu\text{-bar}$, decays from stored muons





vStorm as an R&D platform

- A high-intensity pulsed muon source
- $100 < p_\mu < 300$ MeV/c muons
 - Using extracted beam from ring
 - 10^{10} muons per 1 μ sec pulse
- Beam available simultaneously with physics operation
- A platform to test instrumentation for characterizing high intensity muon beams

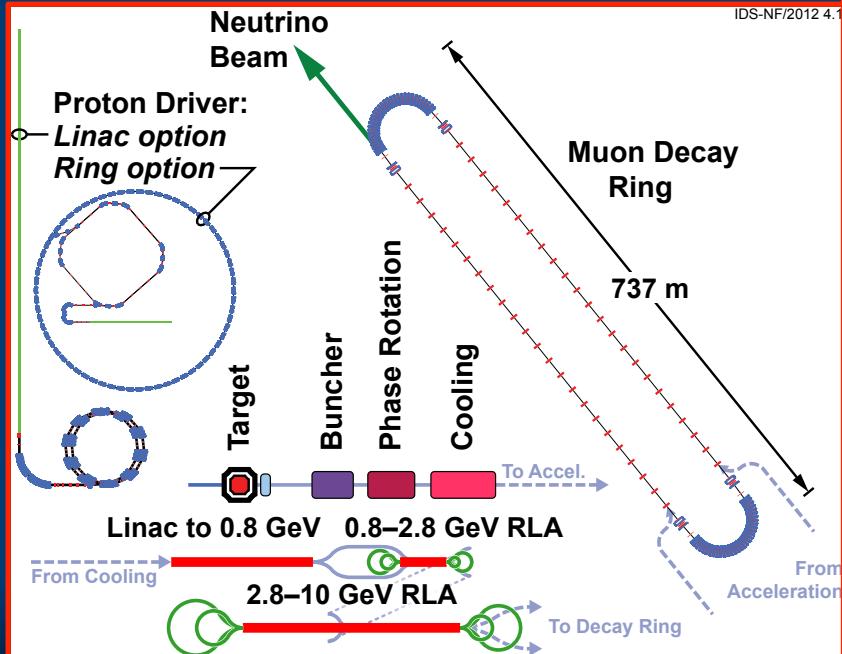




The Long Baseline Neutrino Factory

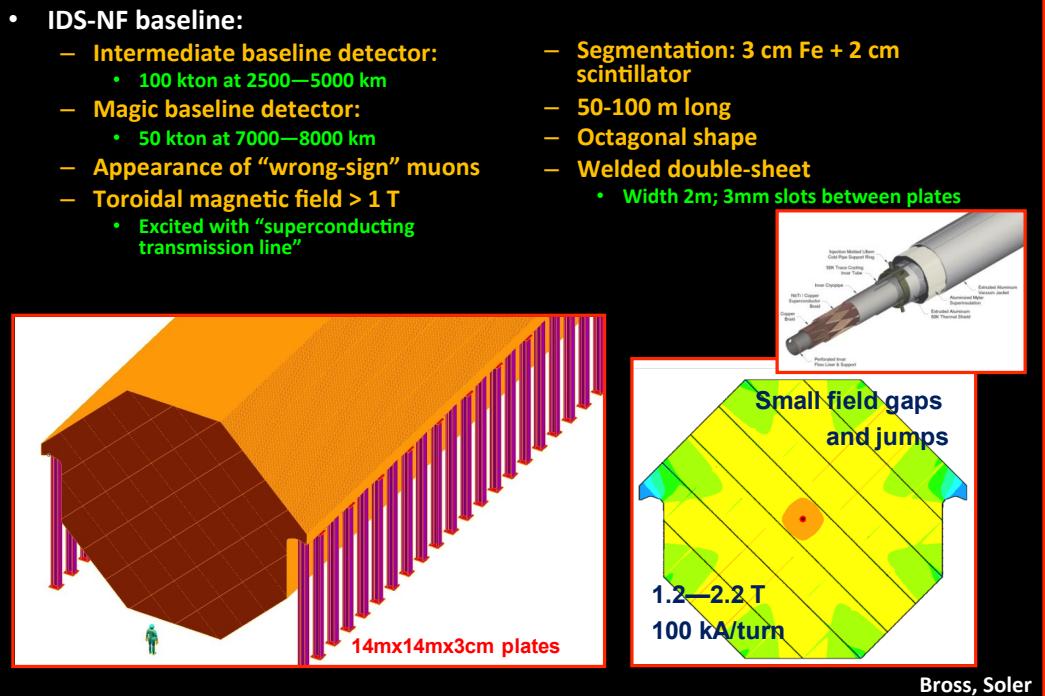
- IDS-NF: the *ideal* NF
- Muon Accelerator Staging Study:

An incremental approach - NuMAX@5 GeV \Rightarrow SURF



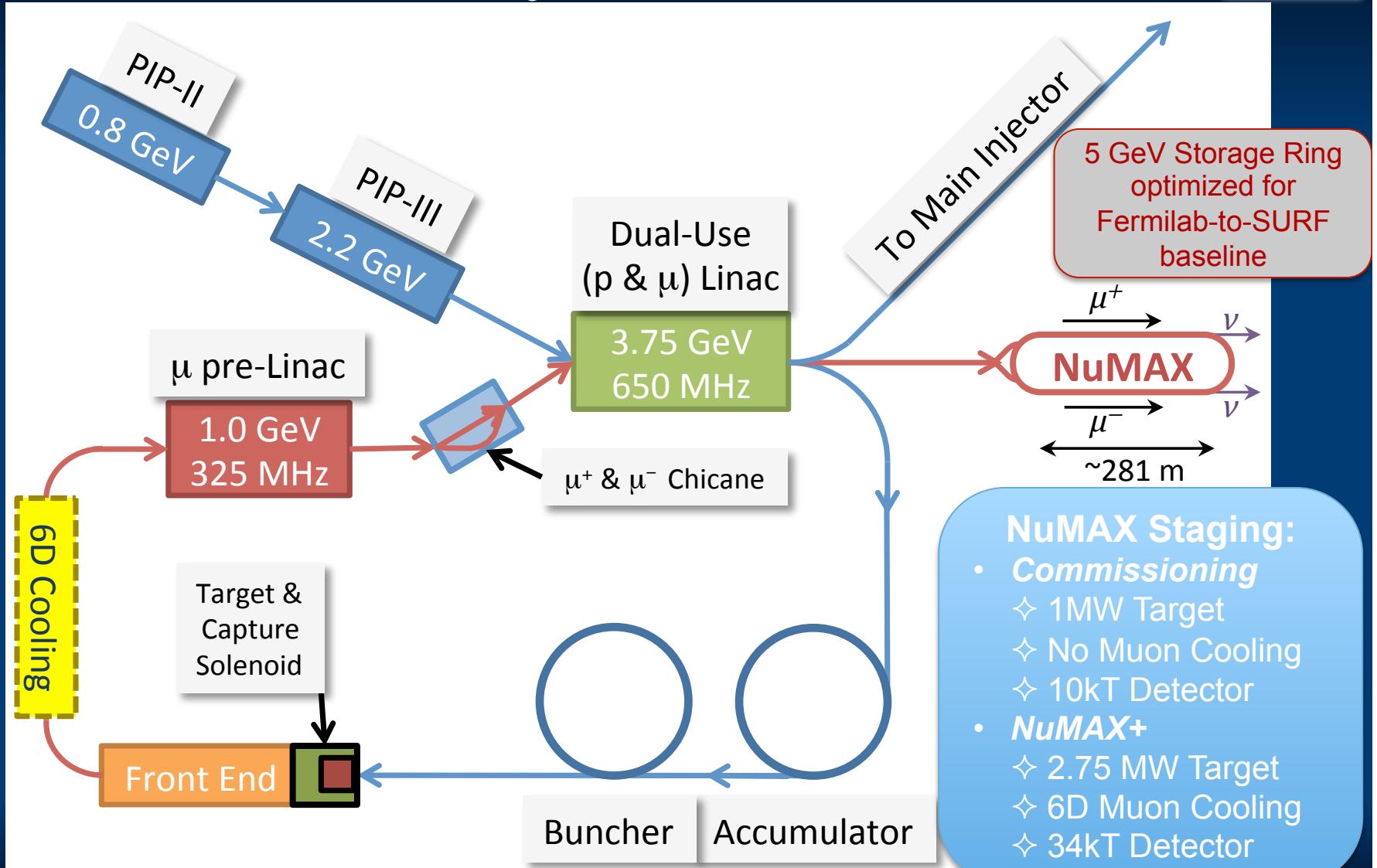
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

Magnetized Iron Neutrino Detector (MIND):





The MAP Muon Accelerator Staging Study ⇔ NuMAX

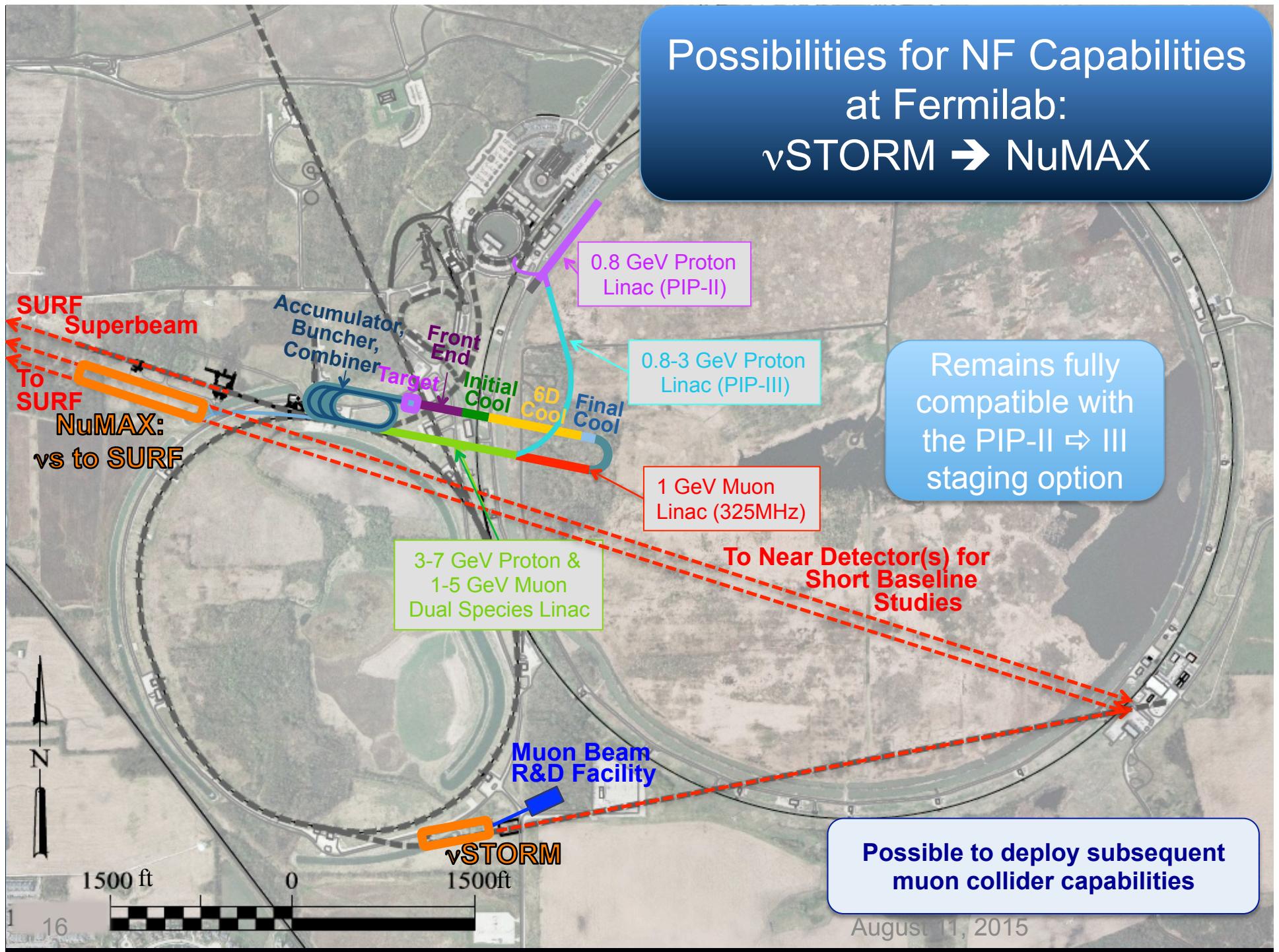




MASS NF Parameters

Neutrino Factory Parameters					
Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
Stored μ^+ or μ^- /year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Far Detector:	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
Distance from Ring	km	1.9	1300	1300	1300
Mass	kT	1.3	100 / 30	100 / 30	100 / 30
Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
Near Detector:	Type	SuperBIND	Suite	Suite	Suite
Distance from Ring	m	50	100	100	100
Mass	kT	0.1	1	1	2.7
Magnetic Field	T	Yes	Yes	Yes	Yes
Accelerator:					
Ring Momentum (P_μ)	GeV/c	3.8	5	5	5
Circumference (C)	m	480	737	737	737
Ionization Cooling	-	No	No	6D Initial	6D Initial
Proton Beam Power	MW	0.2	1	1	2.75

Possibilities for NF Capabilities at Fermilab: ν STORM \rightarrow NuMAX





GOING BEYOND NEUTRINO FACTORY CAPABILITIES

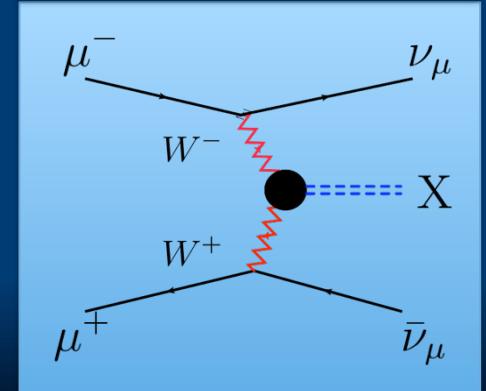
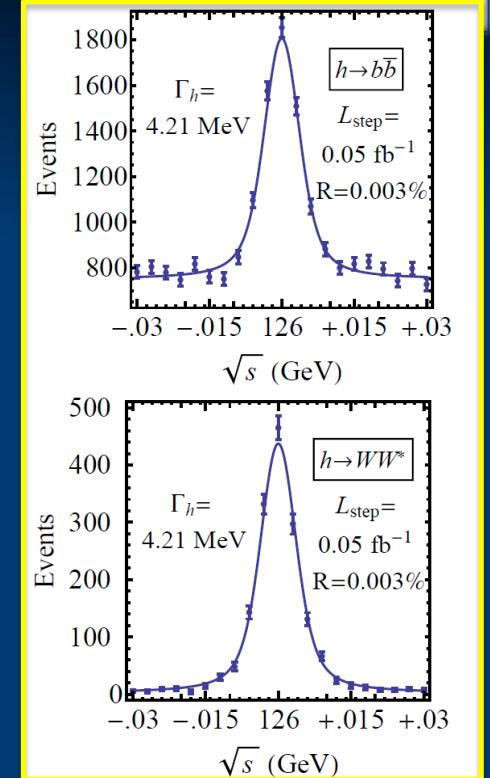


Features of the Muon Collider



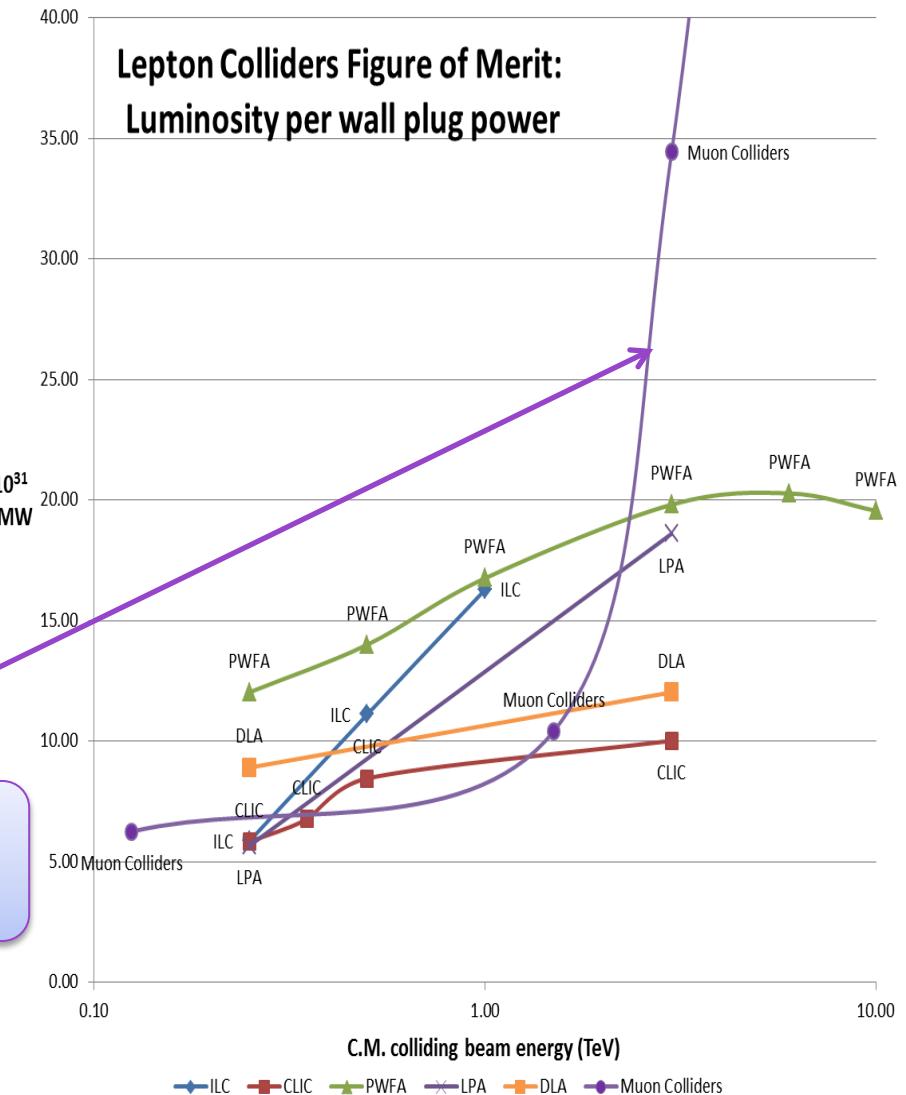
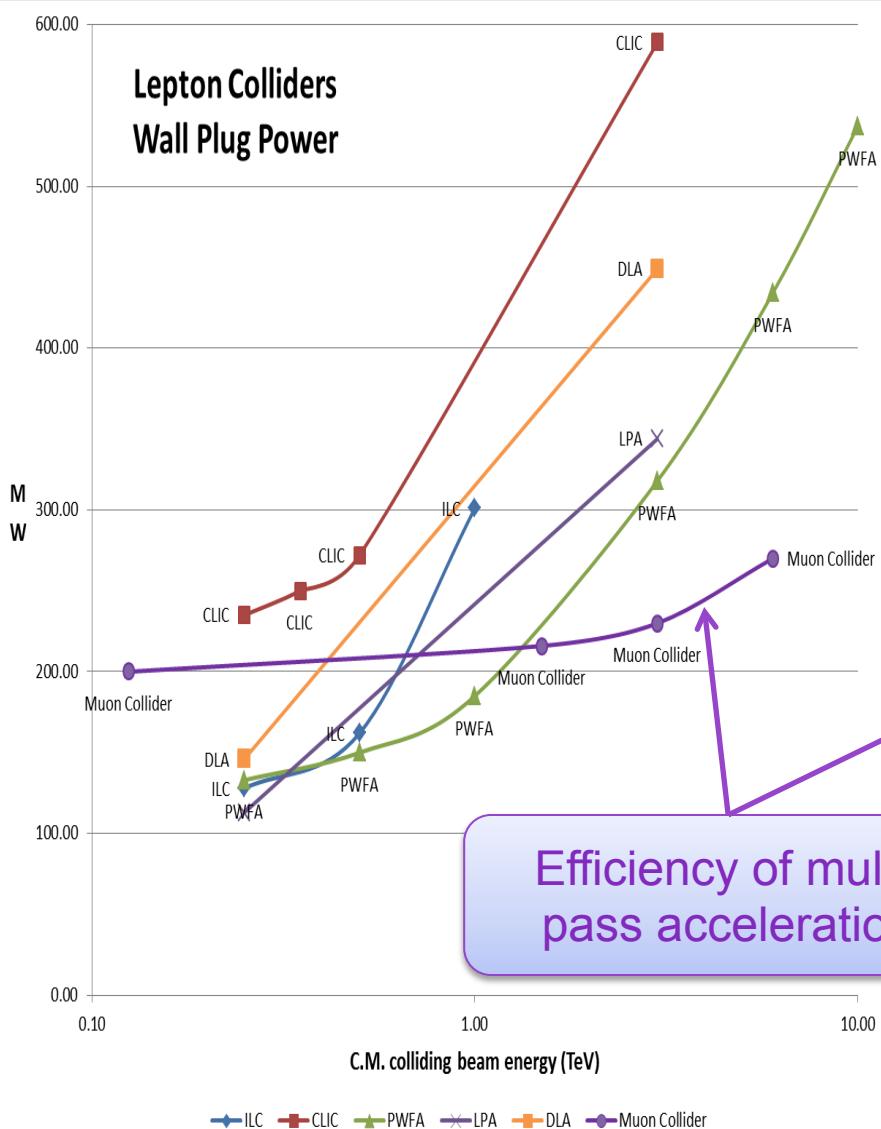
- Superb Energy Resolution
 - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability ($\leq 10\text{TeV}$):
 - Compact & energy efficient machine
 - Luminosity $> 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - Option for 2 detectors in the ring
- For $\sqrt{s} > 1 \text{ TeV}$: Fusion processes dominate
 - ⇒ an Electroweak Boson Collider
 - ⇒ a discovery machine complementary to a very high energy pp collider
 - $> 5\text{TeV}$: Higgs self-coupling resolution $< 10\%$

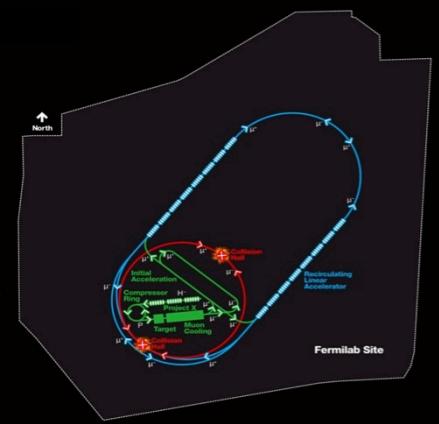
What is our most efficient collider option if new LHC data shows evidence for a multi-TeV particle spectrum?





Muon Colliders – Efficiency at the multi-TeV scale





Muon Collider Parameters

Parameter	Units	Higgs	Multi-TeV			Accounts for Site Radiation Mitigation
		Production Operation				
CoM Energy	TeV	0.126	1.5	3.0	6.0	
Avg. Luminosity	$10^{34} \text{ cm}^{-2} \text{s}^{-1}$	0.008	1.25	4.4	12	
Beam Energy Spread	%	0.004	0.1	0.1	0.1	
Higgs Production/ 10^7 sec		13,500	37,500	200,000	820,000	
Circumference	km	0.3	2.5	4.5	6	
No. of IPs		1	2	2	2	
Repetition Rate	Hz	15	15	12	6	
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25	
No. muons/bunch	10^{12}	4	2	2	2	
Norm. Trans. Emittance, ε_{TN}	$\pi \text{ mm-rad}$	0.2	0.025	0.025	0.025	
Norm. Long. Emittance, ε_{LN}	$\pi \text{ mm-rad}$	1.5	70	70	70	
Bunch Length, σ_s	cm	6.3	1	0.5	0.2	
Proton Driver Power	MW	4	4	4	1.6	
Wall Plug Power	MW	200	216	230	270	

Exquisite Energy Resolution
Allows Direct Measurement
of Higgs Width

Success of advanced cooling
concepts \Rightarrow several $\times 10^{32}$



MUON ACCELERATOR R&D



MAP Accelerator R&D Effort



Design Studies

- Proton Driver
- Front End
- Cooling
- Acceleration and Storage
- Collider
- Machine-Detector Interface
- Work closely with physics and detector efforts

Technology R&D

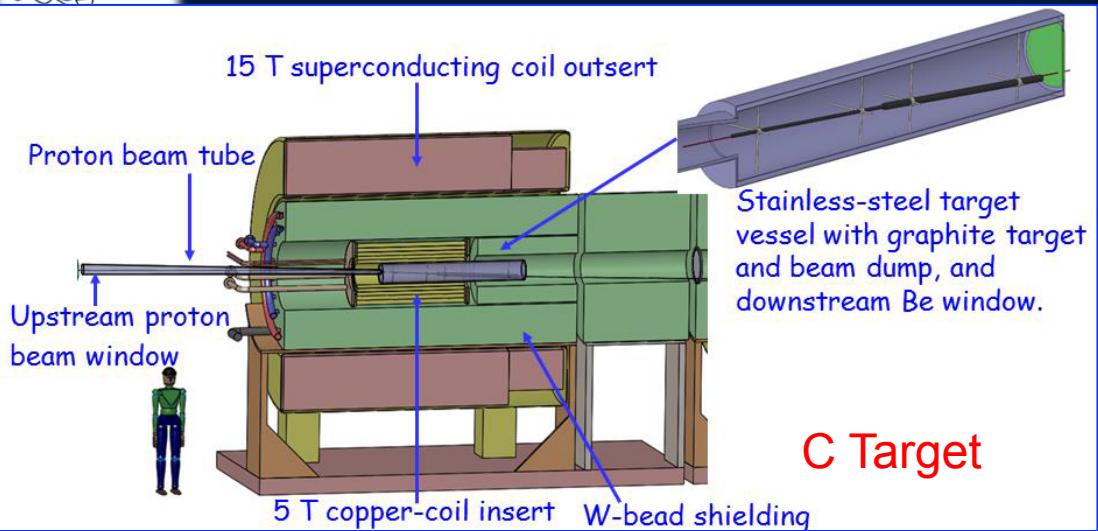
- RF in magnetic fields
- SCRF for acceleration chain (Nb on Cu technology)
- High field magnets
 - Utilizing HTS technologies
- Targets & Absorbers
- MuCool Test Area (MTA)

Major System Demonstrations

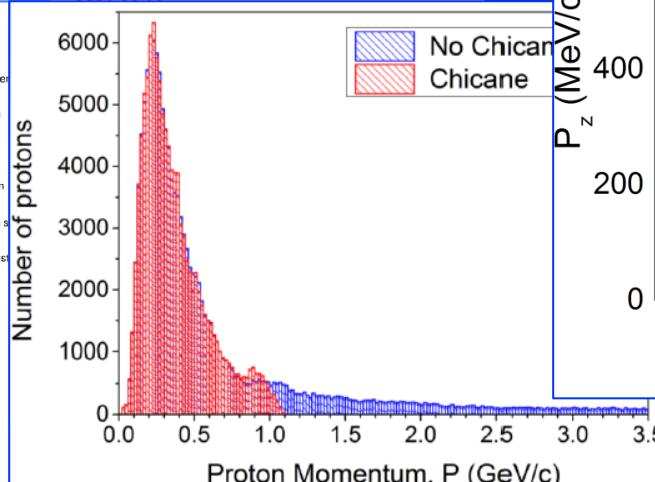
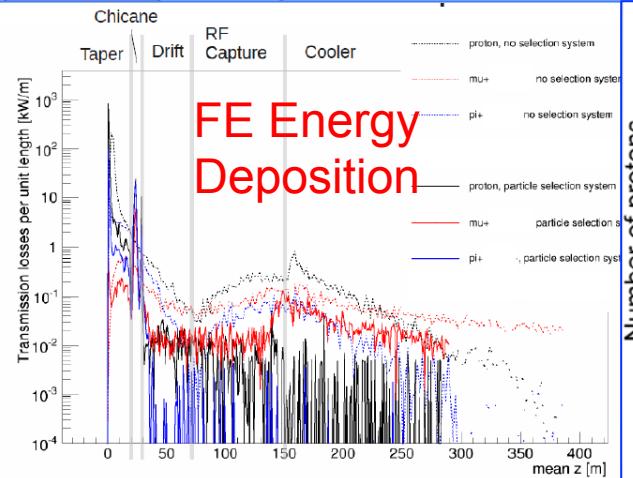
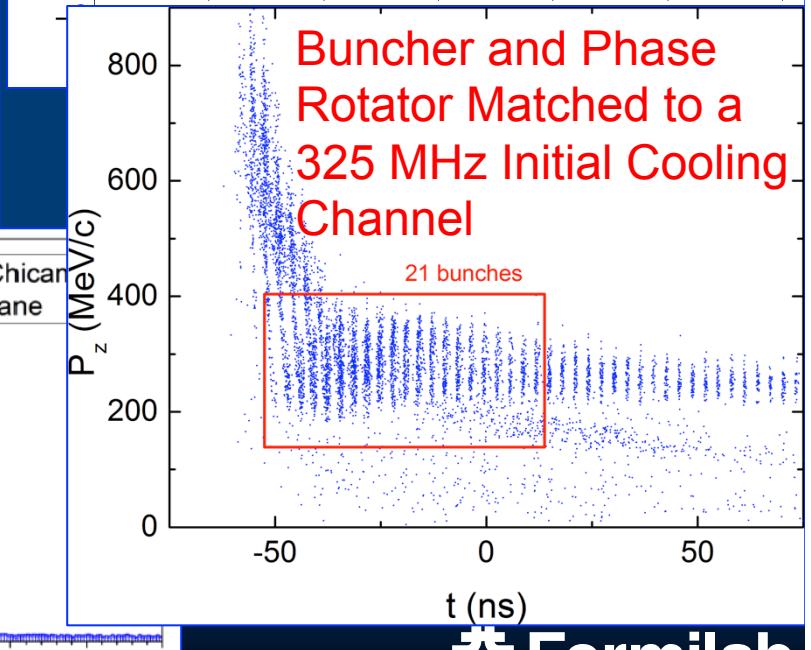
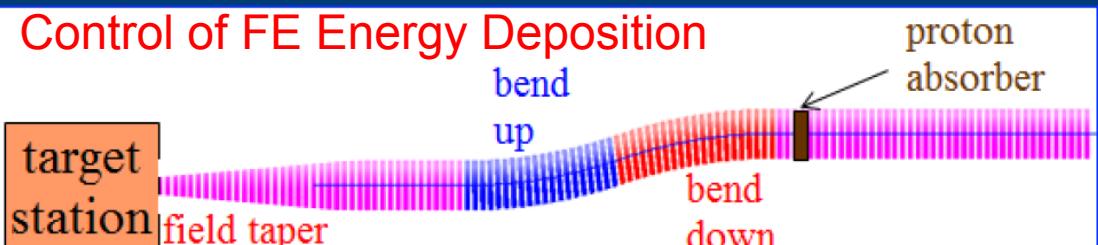
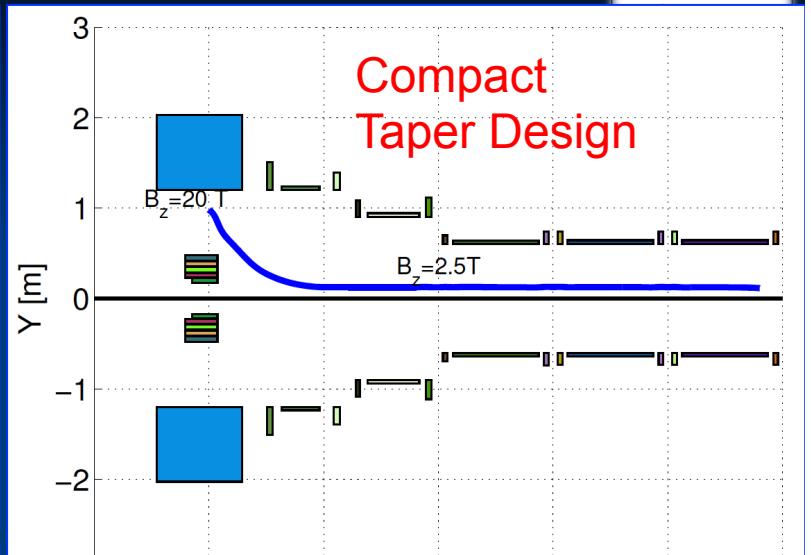
- MERIT – demonstrated the potential of a liquid Hg jet target
- The Muon Ionization Cooling Experiment – MICE



Target & Front End Progress



C Target

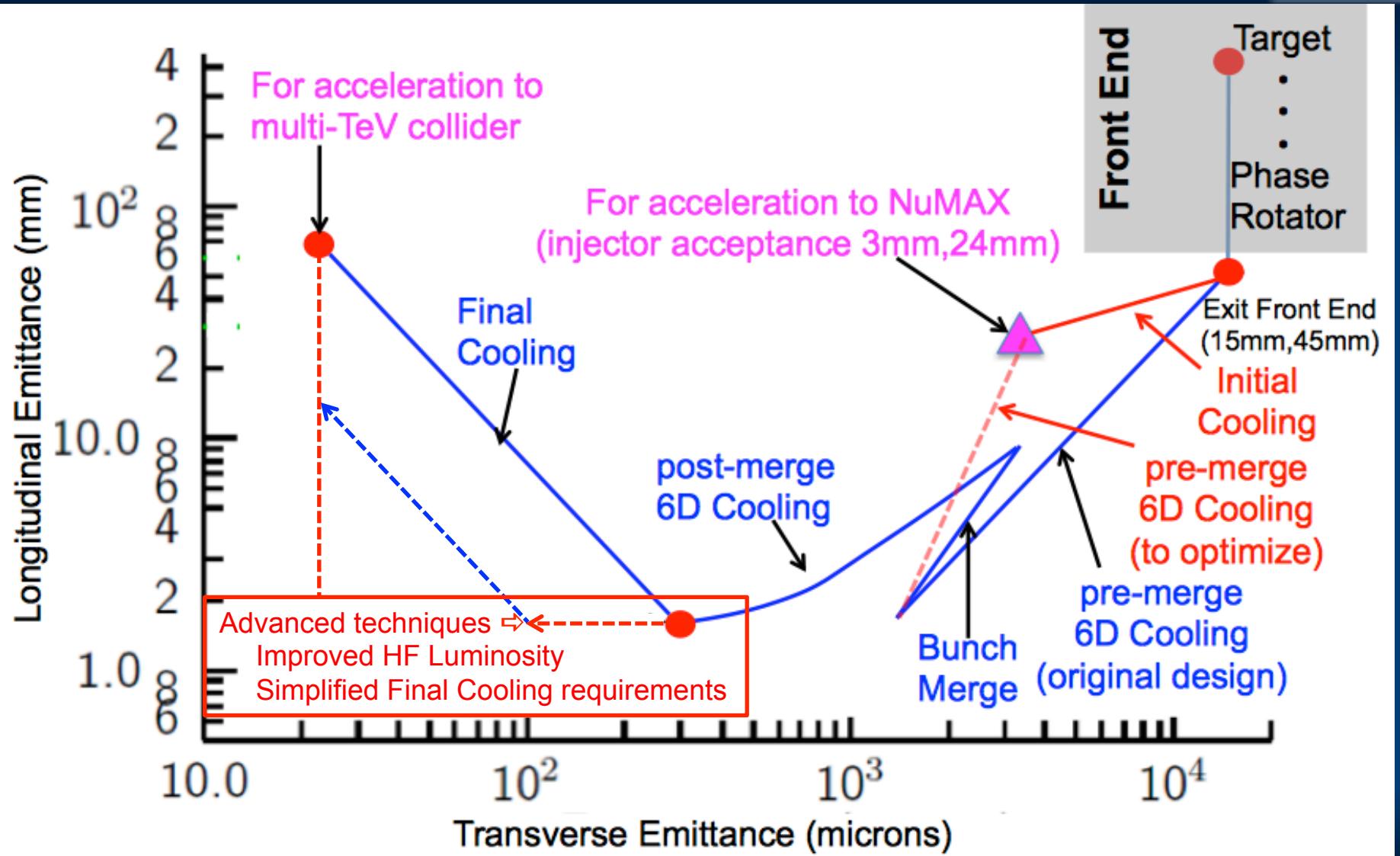


August 11, 2015

Fermilab

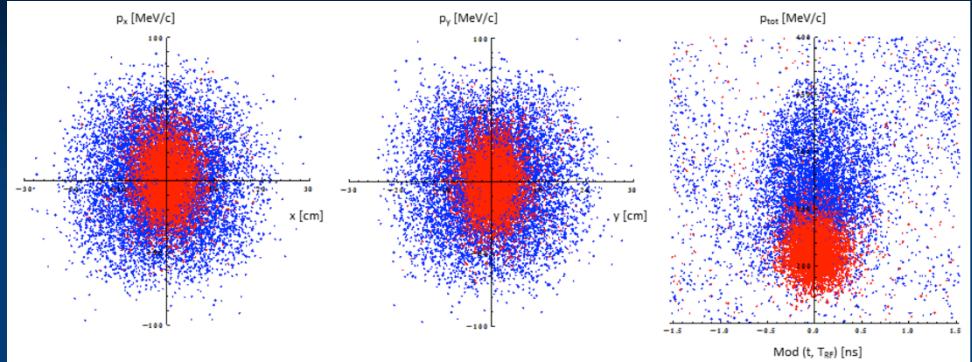
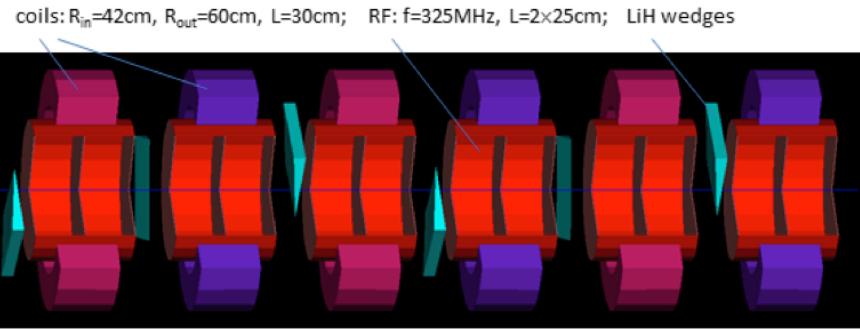


Muon Ionization Cooling

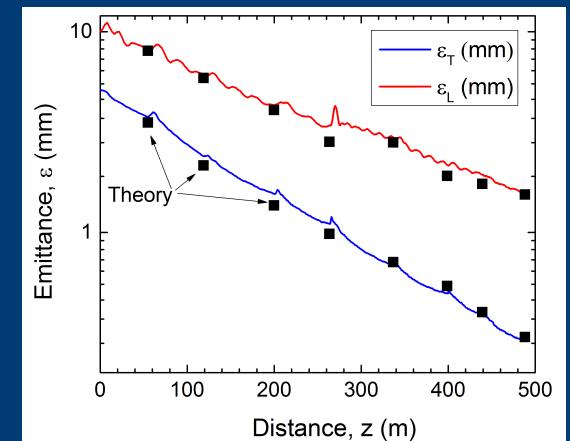
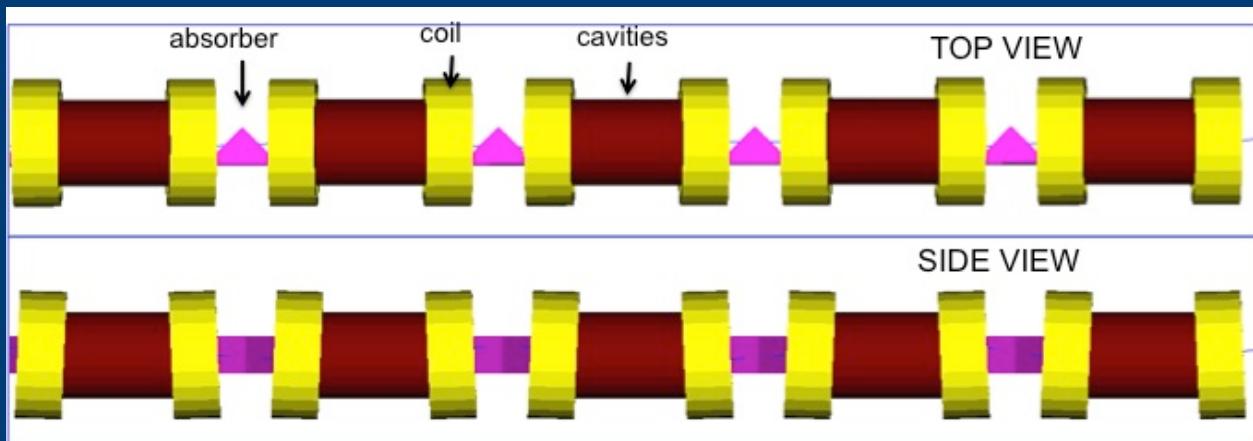




Muon Ionization Cooling (Design)



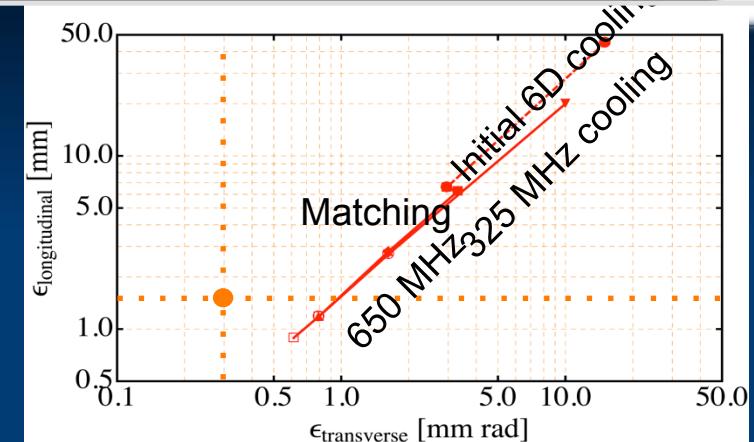
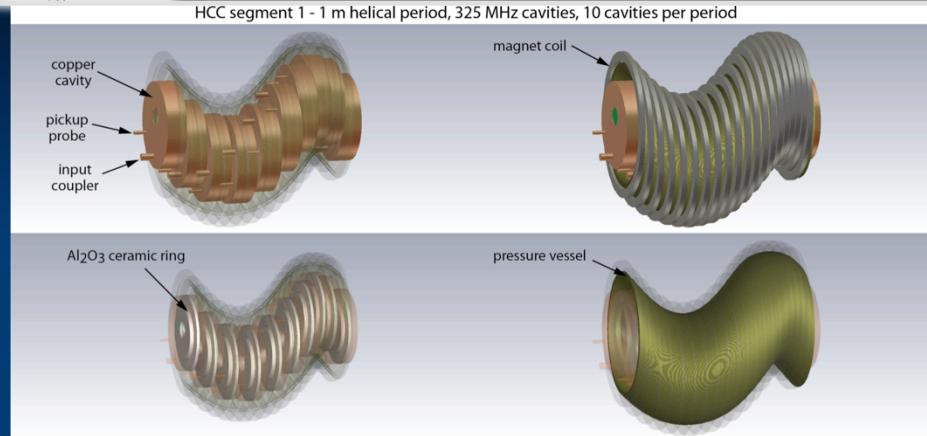
Initial 6D Cooling: $\epsilon_{6D} \quad 60 \text{ cm}^3 \Leftrightarrow \sim 50 \text{ mm}^3$; Trans = 67%



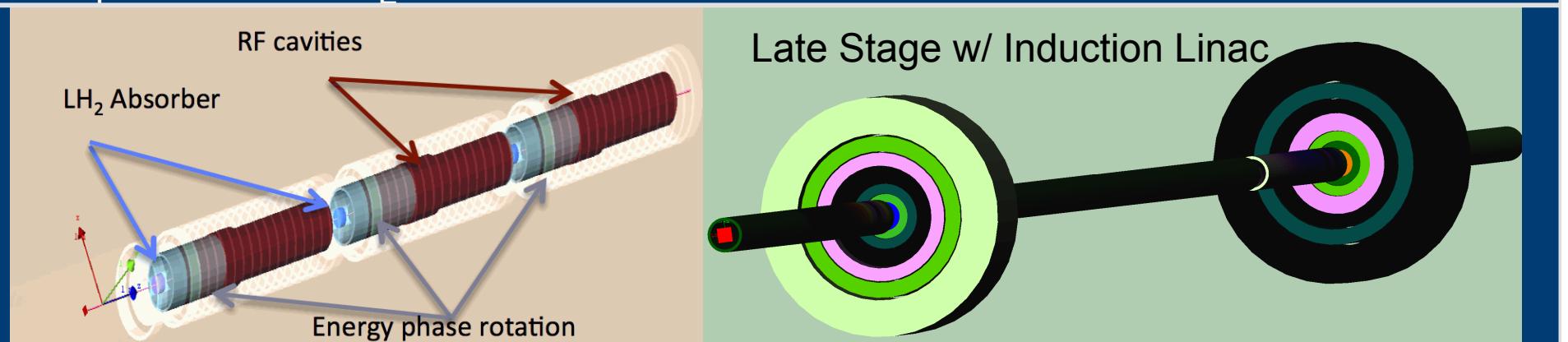
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):
 $\epsilon_T = 0.28\text{mm}$, $\epsilon_L = 1.57\text{mm}$ @488m
Transmission = 55%(40%) without(with) bunch recombination



Muon Ionization Cooling (Design)



- Helical Cooling Channel (Gas-filled RF Cavities):
 $\epsilon_T = 0.6\text{mm}$, $\epsilon_L = 0.3\text{mm}$



- Final Cooling with 25-30T solenoids (emittance exchange):
 $\epsilon_T = 55\mu\text{m}$, $\epsilon_L = 75\text{mm}$

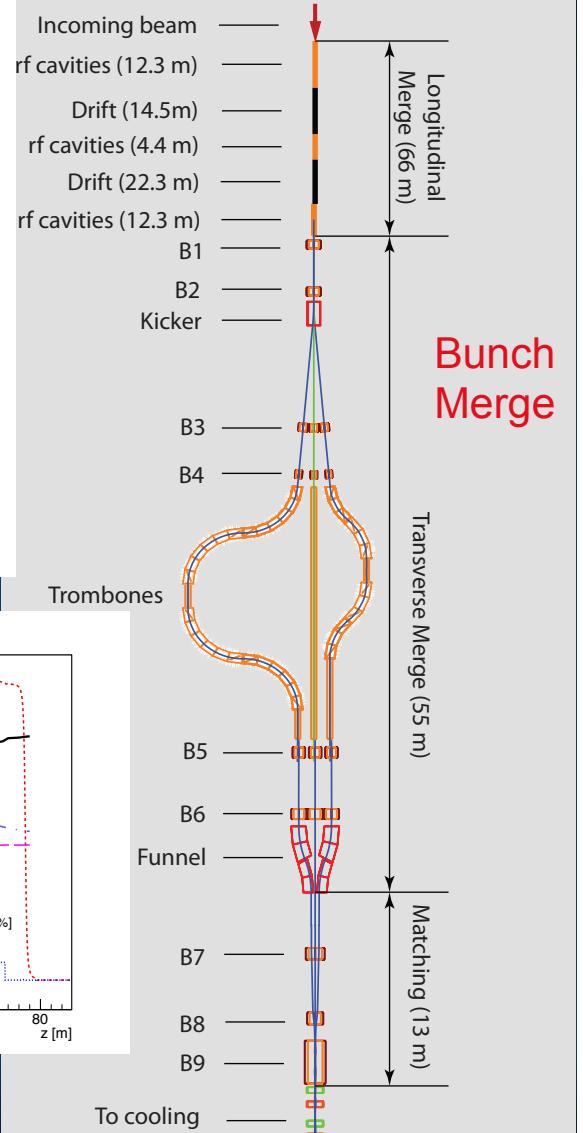
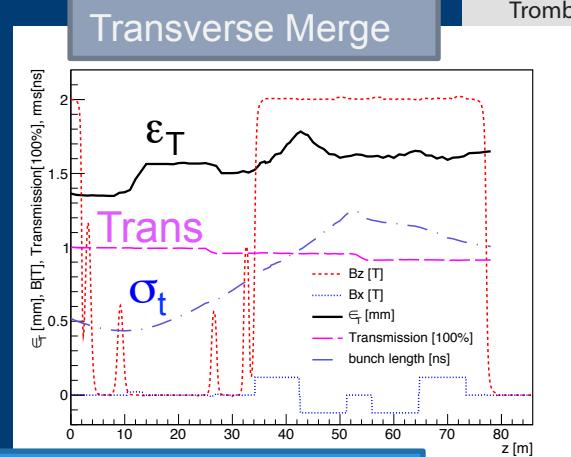
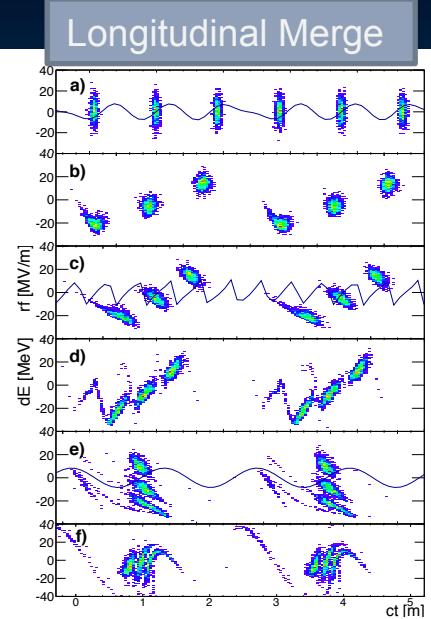


Muon Ionization Cooling (Design)



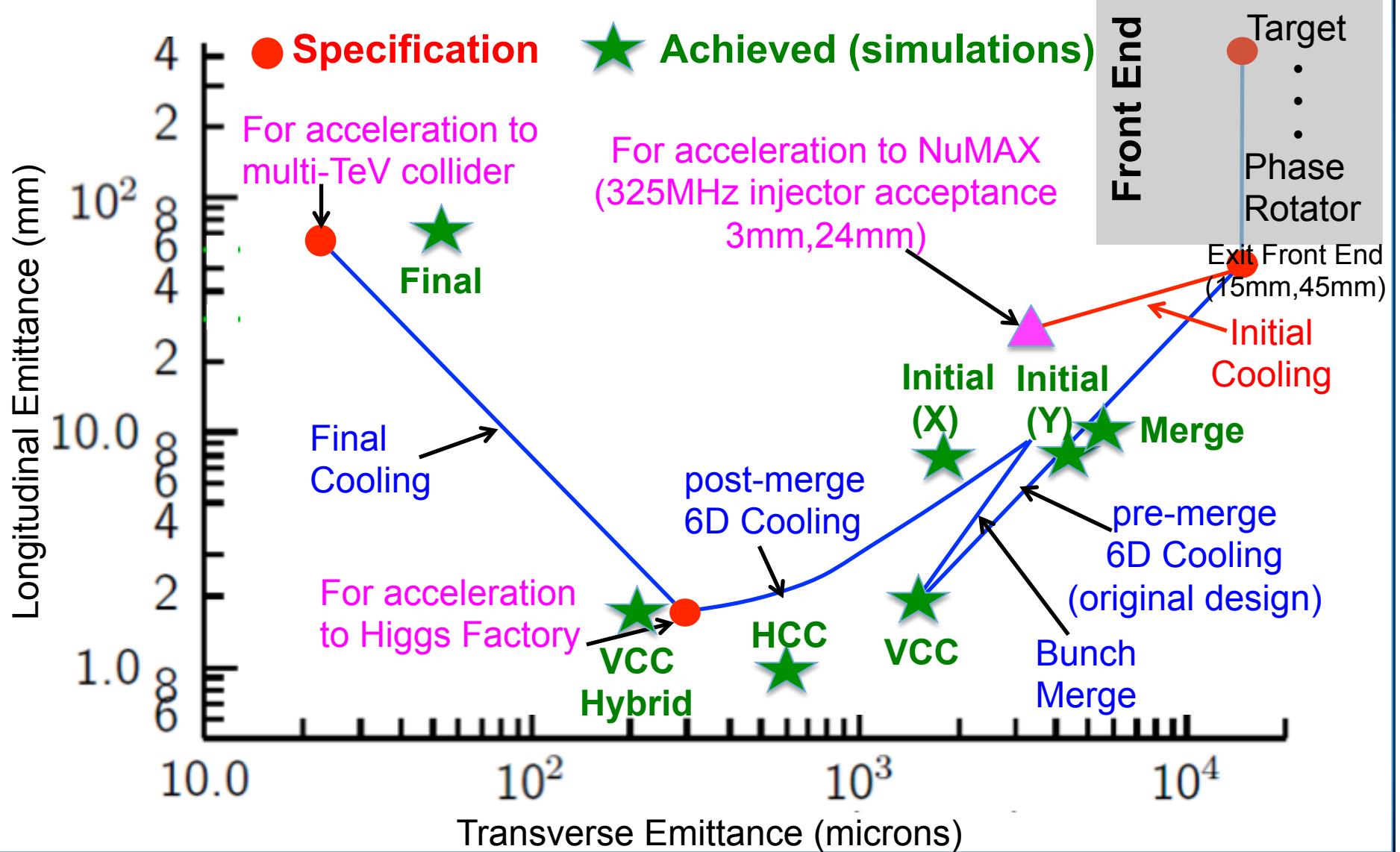
Bunch Merge →

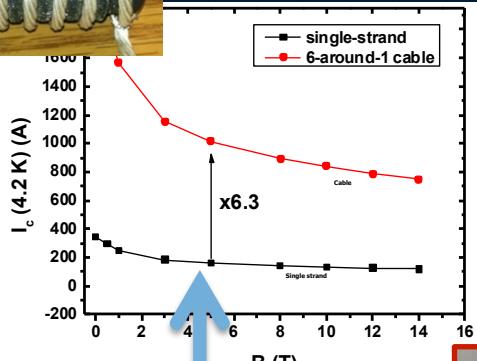
- MAP Baseline Designs offer
 - Factor $>10^5$ in emittance reduction
- Alternative and Advanced Concepts
 - Hybrid Rectilinear Channel (gas-filled structures)
 - Parametric Ionization Cooling
 - Alternative Final Cooling
 - ⇒ Early stages of existing scheme
 - ⇒ Round-to-flat Beam Transform
 - ⇒ Transverse Bunch Slicing
 - ⇒ Longitudinal Coalescing (at ~ 10 s of GeV)
- ⇒ Considerable promise to exceed our original target parameters





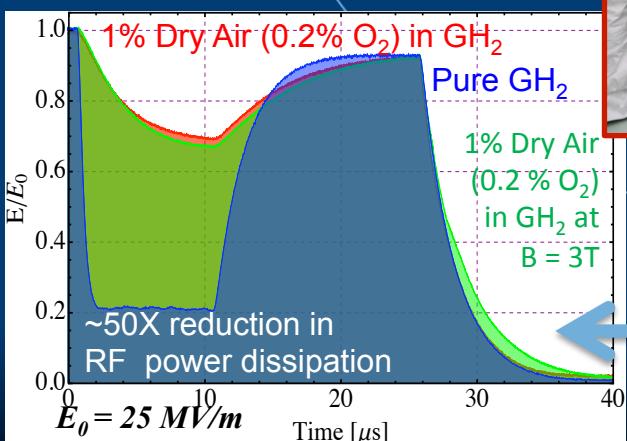
Cooling: The Emittance Path





Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award



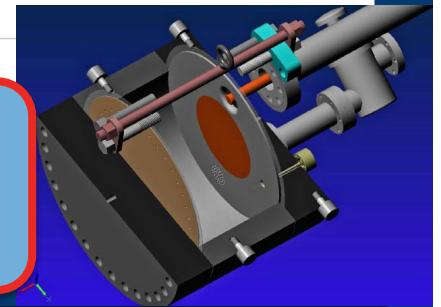
Cooling Technology R&D



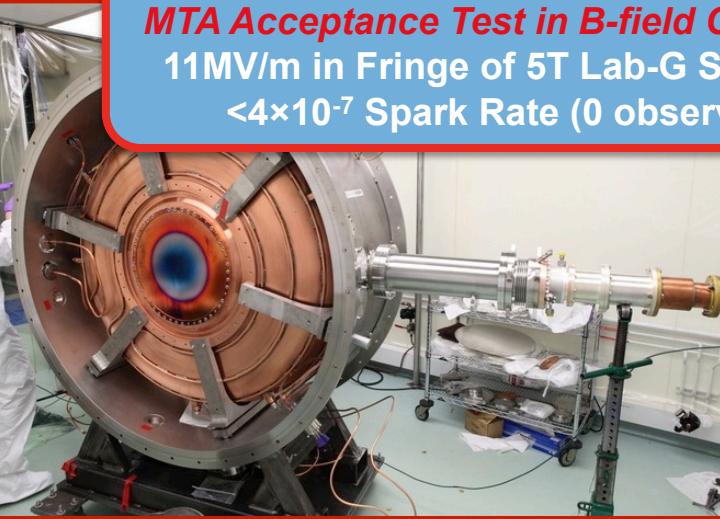
Successful Operation of 805 MHz “All Seasons” Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

>20MV/m operation in up to 5 T B-field



MICE 201 MHz RF Module – MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
<4×10⁻⁷ Spark Rate (0 observed)



World Record HTS-only Coil
15T on-axis field (16T on coil)

R. Gupta
PBL/BNL



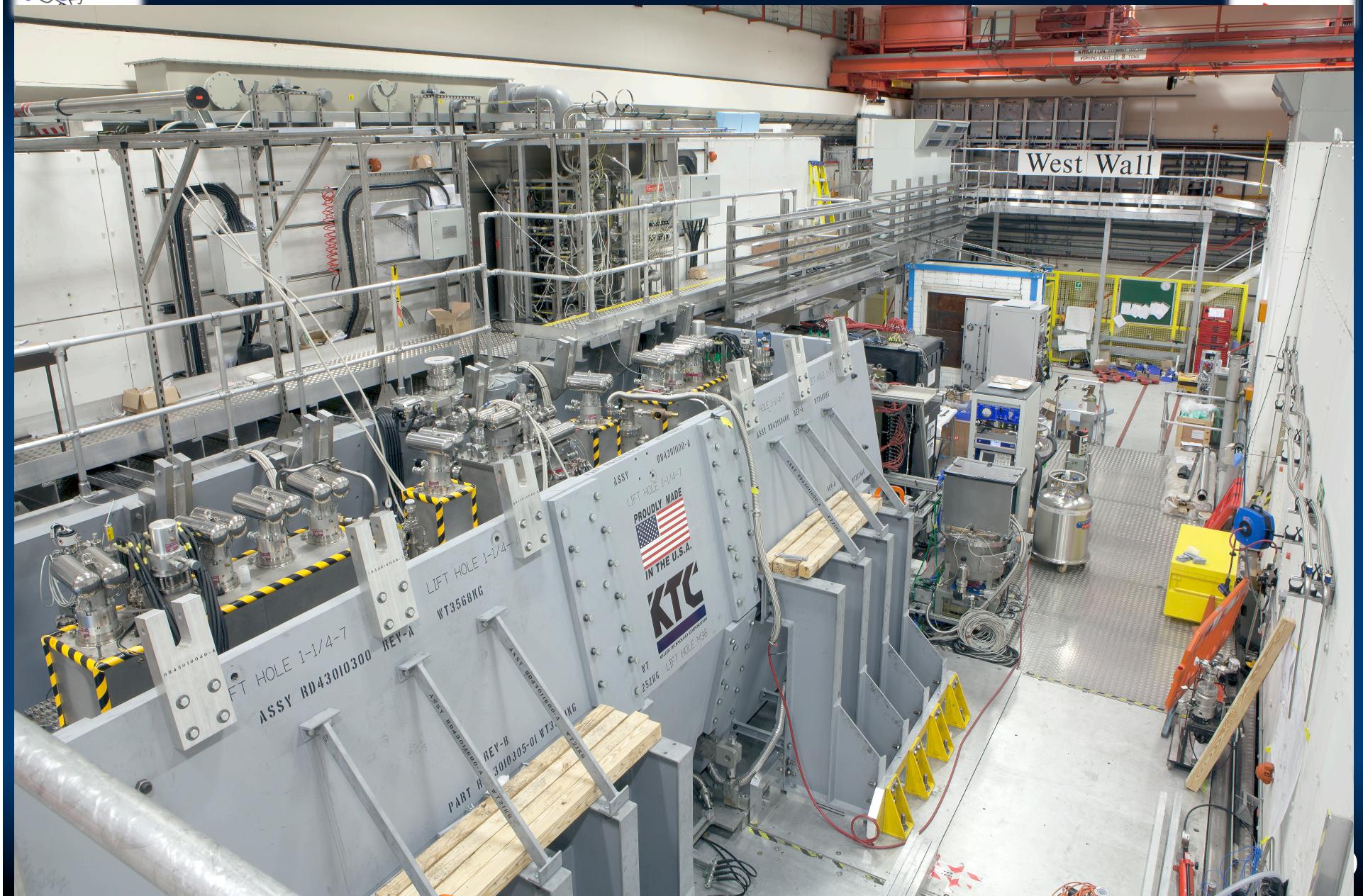
Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam

Extrapolates to required μ-Collider Parameters

MuCool Test Area



Muon Ionization Cooling Demonstration

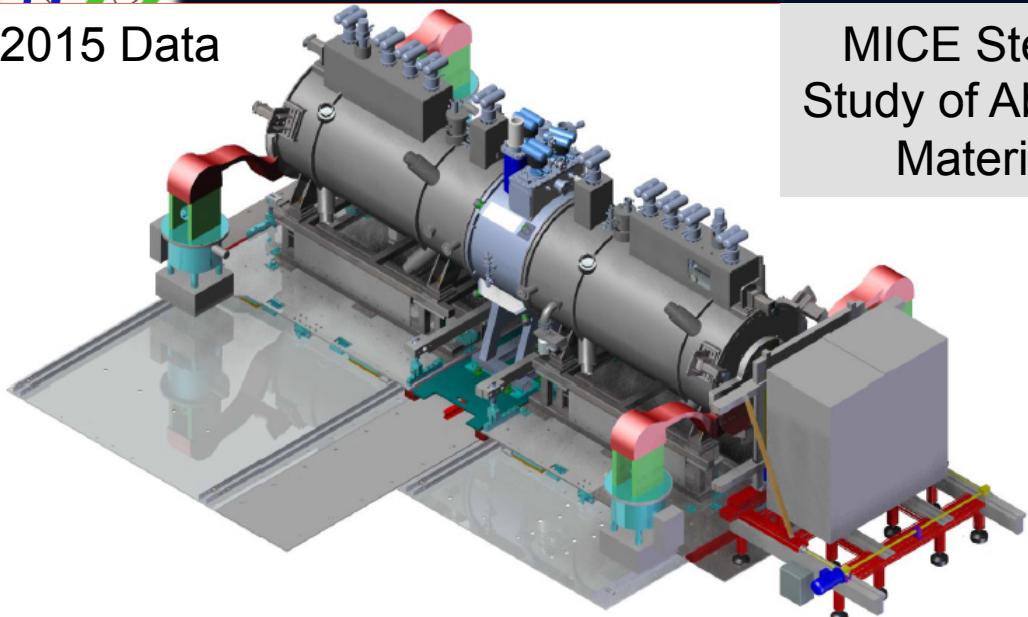




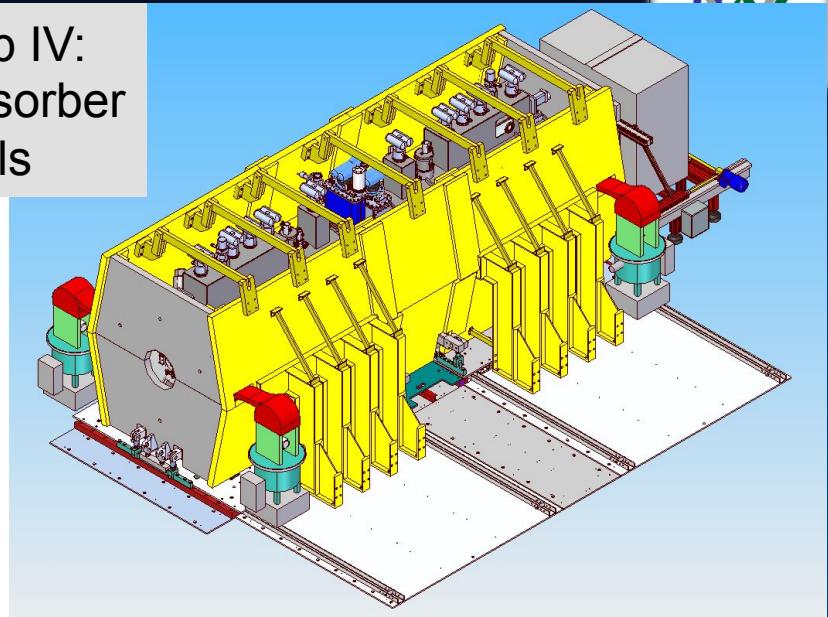
MICE Demonstration @ RAL



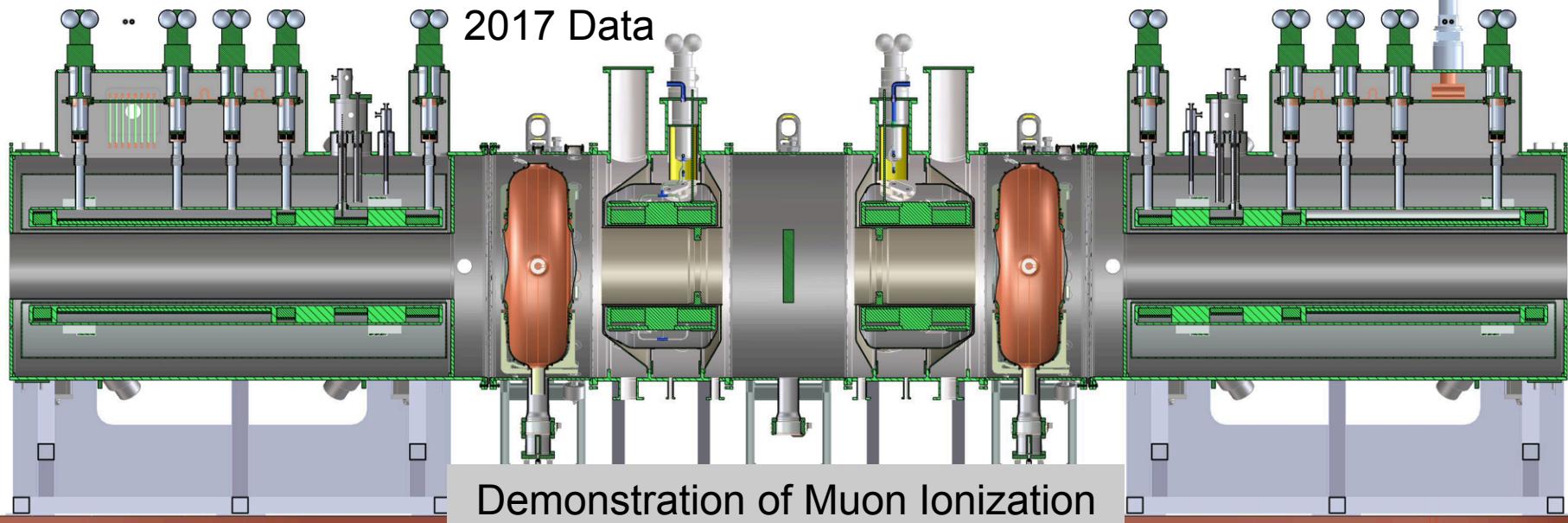
2015 Data



MICE Step IV:
Study of Absorber
Materials



2017 Data

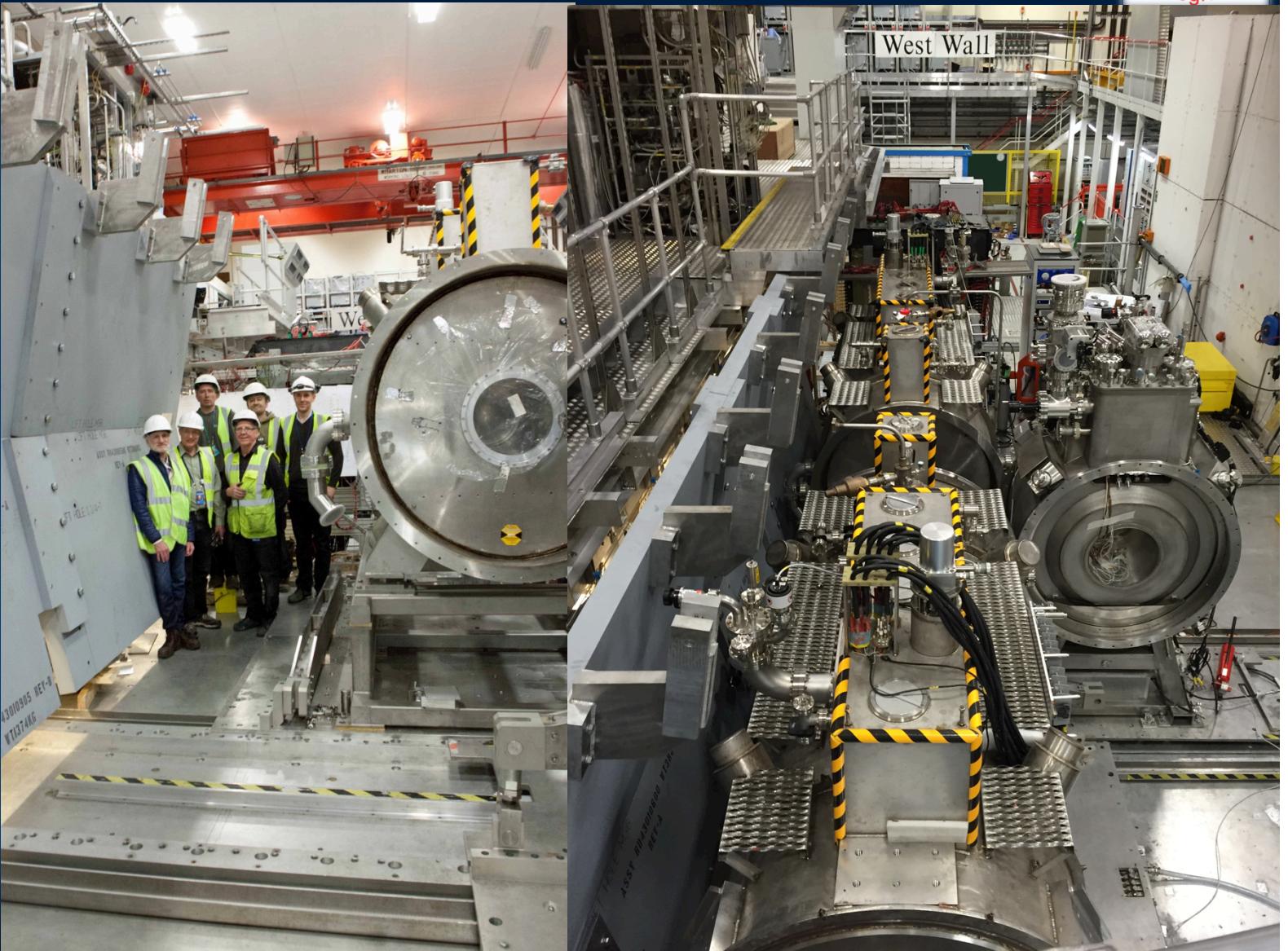


Demonstration of Muon Ionization
Cooling (Re-baseline)



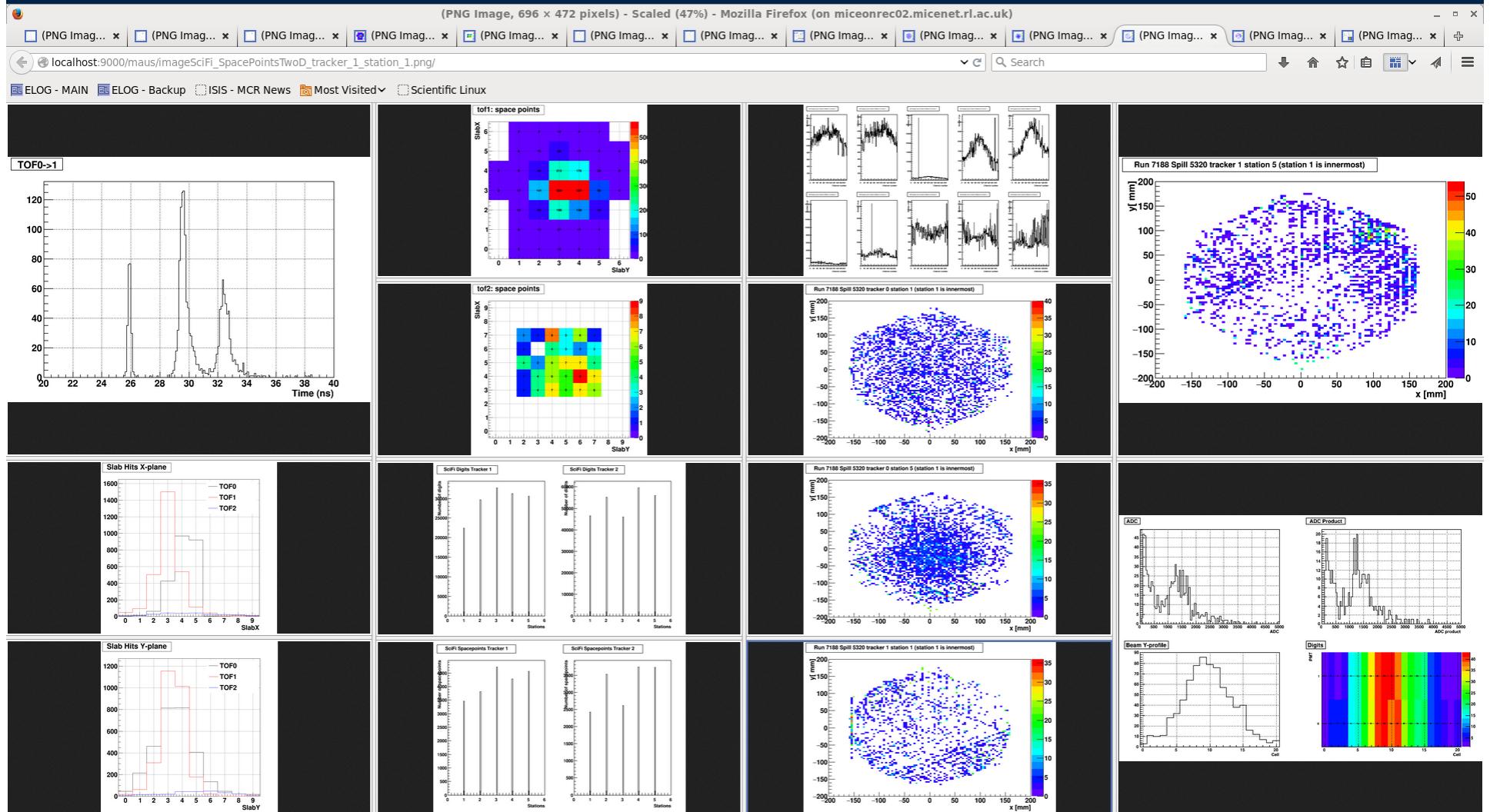
Systems and
Beam
Commissioning
Underway

MICE Installation/Commissioning





MICE Commissioning: Online Reconstruction



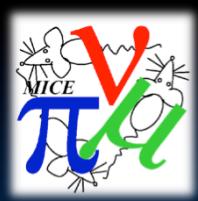


Concluding Remarks



- Neutrino Factory capabilities offer a precision microscope that will likely be needed to fully probe the physics of the neutrino sector
 - Only the neutrino factory route provides detailed conjugate channel studies with a precision source term (flux and purity)
- A multi-TeV muon collider may be the only cost-effective route to lepton collider capabilities at energies > 5 TeV
- For the last 4 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
 - Near-term (ν STORM)
 - *Also beam line techniques to provide higher purity beams \Leftrightarrow nuPIL*
 - Mid-term (NuMAX)
 - Long-term: a muon collider capability that would build on the NF complex
- Key technical hurdles have been/are being addressed
 - Realizable cooling channel designs with acceptable performance
 - Breakthroughs in cooling channel technology
 - The MICE experiment is now being commissioned!

Muon accelerator capabilities offer unique potential for the future of high energy physics research



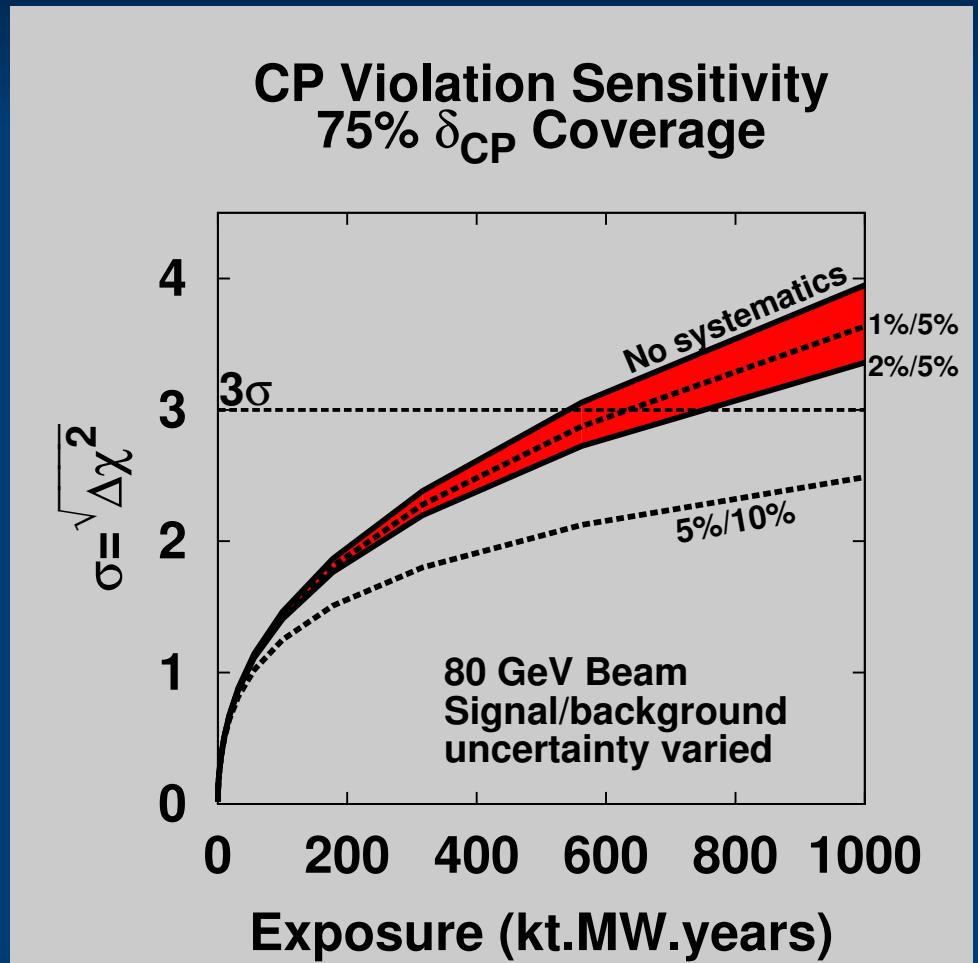
BACKUP SLIDES



nuSTORM and δ_{cp} Coverage @ DUNE



- 75% coverage of δ_{cp} in a LBL ν oscillation experiment (P5 requirement) in a reasonable exposure time
 - ⇒ *Systematic uncertainties at the 1% level are required.*
- Degradation of systematic uncertainties to the ~5% level
 - ⇒ *exposure increase of 200-300% (very non-linear).*
- *We have yet to achieve 2% uncertainty in ν experiments.*



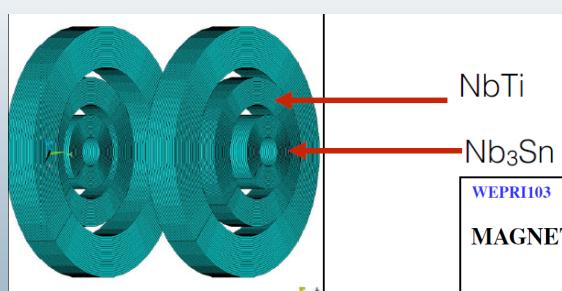
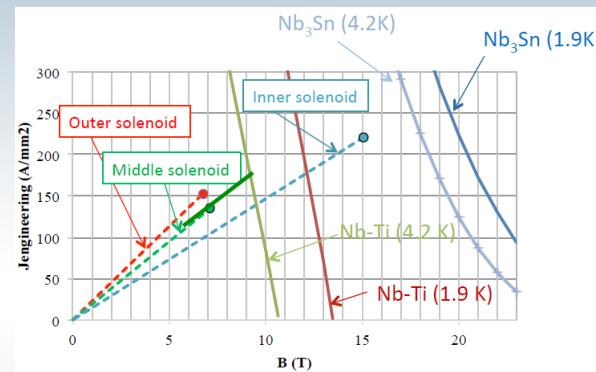
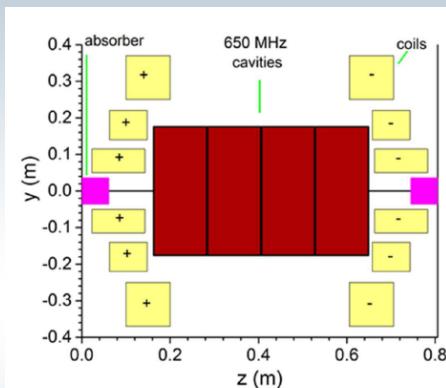


Cooling Technology Status I



- Magnets
 - MAP Initial Baseline Selection (IBS) process
⇒ 6D cooling baselines that do *not* require HTS magnets
 - HTS Solenoids could be part of a higher performance 6D Cooling Channel and for parts of the Final Cooling Channel

Magnet feasibility studies (last stage)



% of the load line at operational current		
Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%
Nb-Ti @ 1.9 K	-	59%
Nb ₃ Sn @ 4.2 K	88%	-
Nb ₃ Sn @ 1.9 K	81%	-

WEPR103

Proceedings of IPAC2014, Dresden, Germany

MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

H. Witte[†], D. Stratakis, J. S. Berg, R. B. Palmer, Brookhaven National Laboratory, Upton, NY, USA
F. Borgnolatti, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

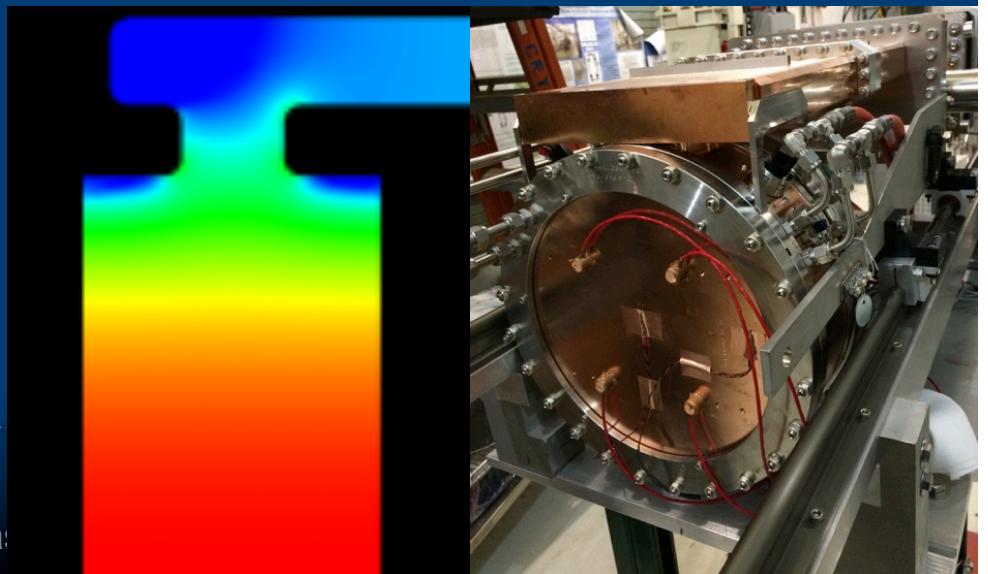
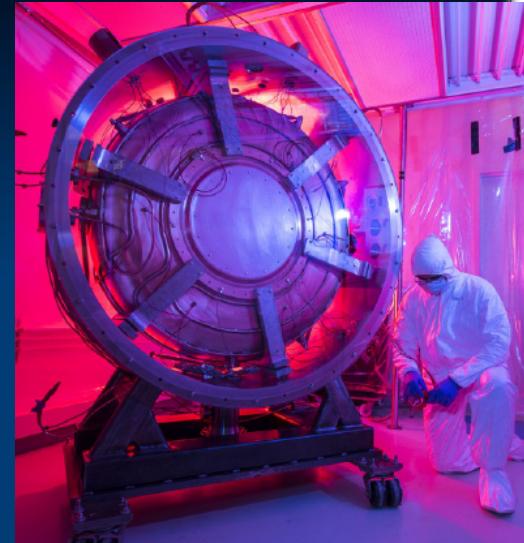


Cooling Technology Status II



- RF Cavities

- *Successful test in magnetic field* of the MICE RF Module shows
 - The importance of cavity surface preparation
 - The importance of designs incorporating detailed magnetic simulation
- High Pressure Gas-Filled RF Cavities provide a *demonstrated route to the required gradients with high intensity beams*
- Vacuum RF: recent B-field tests consistent with our physical models
 - **805 MHz “Modular” Cavity:** *A test vehicle to characterize breakdown effects in vacuum cavities* →





Technology Challenges - Acceleration

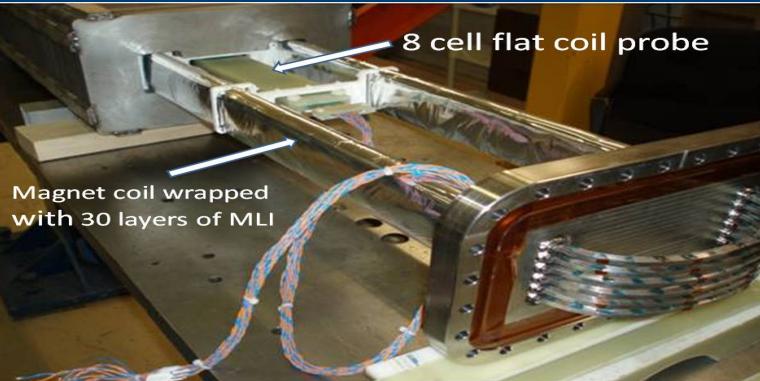


- Muons require an ultrafast accelerator chain
⇒ *Beyond the capability of “standard designs”*
- Solutions include:



EMMA – FFAG

- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- Rapid Cycling Synchrotrons (RCS)



RCS requires
2 T p-p magnets
at $f = 400$ Hz
(U Miss & FNAL)



39 NuFact15 - Centro Brasileiro de Pesquisas Fisicas

JEMMRLA Proposal:
JLAB Electron Model of
Muon RLA with Multi-pass
Arcs

August 11, 2015

 Fermilab



Muon Rings

- NF: nuSTORM, IDS-NF and NuMAX designs
- Collider: Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
 - With supporting magnet designs and background studies
 - Detector occupancy similar to that seen in the LHC Luminosity Upgrade

